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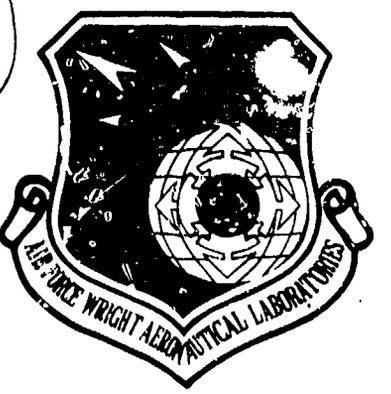

IMPROVED PENETRANT PROCESS EVALUATION CRITERIA

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October 1981

Final Report for Period 1 August 1980 - 31 July 1981

Materials Laboratory
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Wright-Patterson Air Force Base, Ohio 45433

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This technical report has been reviewed and is approved for publication.

James A. Holloway

JAMES A. HOLLOWAY
Project Engineer

FOR THE COMMANDER

D. M. FORNEY, Jr., Chief
Nondestructive Evaluation Branch
Metals and Ceramics Division

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The objective of this program is to investigate the significance of the improvements and modifications suggested in "Methods Improvement of the Fluorescent Penetrant Inspection (FPI) Process." The program is composed of three technical phases: (I) specimen preparation and baseline demonstration, (II) improved methods demonstration, and (III) statistical comparison of Phase I and Phase II.

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PREFACE

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This report is submitted in accordance with the requirements of AFWAL Contract F33615-80-C-5060 and represents the final technical report covering the period of 1 August 1980 — 31 July 1981. Mr. J. A. Holloway, AFWAL/MLLP was the Air Force Project Engineer. The program was conducted under the cognizance of M. C. VanWanderham, General Supervisor of the Mechanics of Materials and Structures section of the Materials Engineering and Technology Department at the Pratt & Whitney Aircraft Group, Government Products Division (P&WA/GPD), West Palm Beach, Florida.

The Principal Investigator was K. D. Smith and the Program Manager was J. S. Cargill, reporting to J. A. Harris.

The authors gratefully acknowledge the technical contributions of several individuals in the Materials Engineering and Technology Department: B. A. Cowles, E. J. Drumheller and J. Rieck. The assistance of Mr. J. Garcia and Mr. R. Samsel of Kelly Air Force Base is greatly appreciated as their cooperation made the demonstrations possible.

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SECTION I

INTRODUCTION

The modifications suggested in "Methods Improvement of the Fluorescent Penetrant Inspection Process" (Contract F33615-79-C-5021) (Ref. 1) were tested in this program to determine if they improve the inspection process. The modified surface preparation procedures and process parameters suggested in "Methods Improvement" were compared to a baseline state-of-the-art method of surface preparation and processing. The baseline surface preparation procedures were those suggested in USAF T.O. 2J-TF39-3 (Ref. 2) as well as NAVAIR 02-1-517/T.O. 2-1-111/DMWR 55-2800-206 (Ref. 3). These technical orders are available at the Air Logistics Centers (ALCs) and can be used on both types of materials under consideration. The specific surface preparation modification suggested is a chemical milling procedure to remove a shallow smear metal layer, approximately 0.00254 mm to 0.00381 mm (0.0001" — 0.00015"). Modified surface preparations improved detectability over the baseline procedures. The modified process parameters, which consisted of hydrophilic emulsifier and wet, water soluble developer, increased the brightness of the indications.

A. BACKGROUND

Improved fluorescent penetrant inspection (FPI) is of major concern to the United States Air Force, especially for advanced, high performance aeropropulsion systems which utilize components to their ultimate capacity. As the life cycle costs of these components have been steadily increasing due to the use of advanced materials and processing techniques, design complexities, and material and energy shortages, the need to extract the full safe life from every component has increased dramatically. Eventually, the strategic materials currently used in high performance aircraft engines may become difficult to procure at any cost, forcing manufacturers and consumers to conserve through the total use of these materials.

The FPI process is one of the most important inspection tools utilized by the Air Force. The sensitivity and reproducibility of this process is largely controlled by the manner in which several critical steps are carried out and by the control of several process variables. The basic procedure for performing FPI is shown in Figure 1. It is imperative that the sensitivity and reliability of FPI be improved in order to achieve the flaw detection capability necessary to meet future requirements.

Although FPI is the most widely used inspection technique for engine components, its apparent simplicity is deceptive and can lead to a false belief in infallibility, resulting in a tendency to overlook the basic requirements leading to a good inspection. The apparent simplicity of the FPI process has hindered research into improvements of the processing techniques until recently. Studies have been conducted in the area of airframe components, but the materials and flaw sizes of airframes present different problems than those encountered in engine components. Generally, the critical crack sizes are smaller in engine components than in airframe components. Additionally, engine components are subjected to severe environmental conditions and very high temperatures during engine operation. All of these factors make it very difficult for FPI to detect tight fatigue cracks.

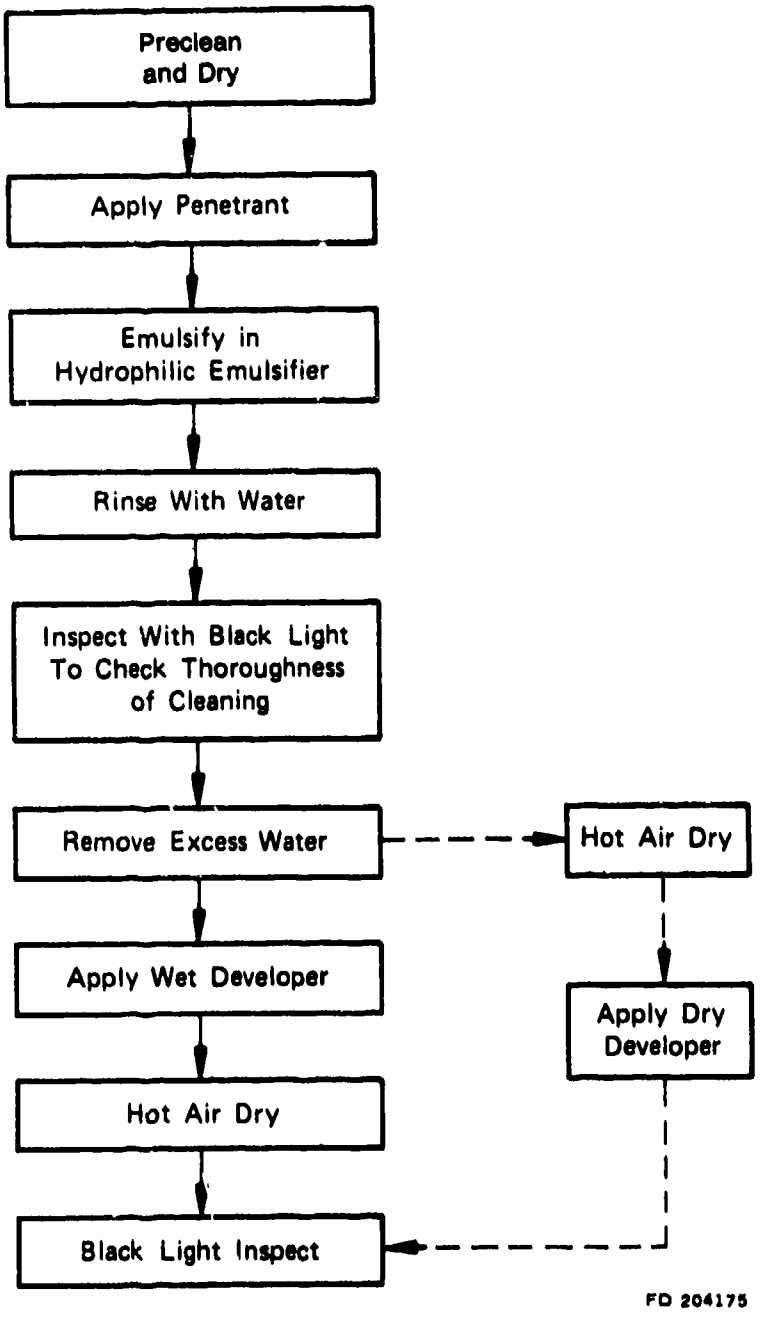


Figure 1. Fluorescent Penetrant Inspection Procedure

A previous P&WA GPD/AFML contract, "Methods Improvement of the Fluorescent Penetrant Inspection Process," explored improved surface preparation procedures as well as improved process parameters to increase the inspection capability at engine maintenance facilities. Improved surface preparation procedures were directed at removing simulated engine contamination that state-of-the-art chemical cleaning procedures would not remove. The end result was to remove the remaining contamination mechanically with a light vapor blast (30 seconds, 40.6-45.7 cm (16 to 18 in), 6.89×10^5 Pa (100 psi)) and then remove the resulting smear metal with a general chemical milling procedure. The vapor blast reduced background fluorescence through the removal of surface contamination which may trap penetrant.

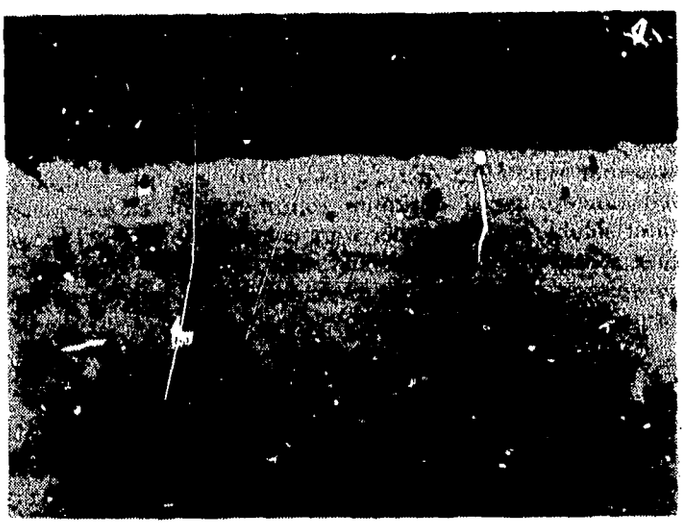
A uniform surface deformation (See Figure 2) is provided by vapor blasting, more so than grit blasting; however, the surface metal can be smeared over a surface crack even with a vapor blast. To remove the smear metal, an etch was found which would not selectively attack the metal, but would evenly remove or mill the metal surface. An LCF and creep study was performed to evaluate the effect of the chemical solutions on these properties. The results of this study indicate that these properties were not degraded by a solution of primarily hydrochloric and nitric acids on Inconel 718 and a nitric/hydrofluoric acid combination on Ti-6Al-4V.

Process parameters including penetrant selection, method of penetrant application, penetrant dwell time, excess penetrant removal and developer application were evaluated. These parameters were varied to determine the optimum combination for high sensitivity with production type applications. During the testing, several brand name water washable penetrants, as well as post emulsifiable penetrants were tested in order to determine which penetrant provided the best sensitivity on the materials under consideration, Inconel 718 and Ti-6Al-4V. Magnaflux ZL-30, a Group VI penetrant, provided the best results of all penetrants tested. Generally, penetrants gain sensitivity with increasing dwell time, provided the penetrant does not dry on the surface of the part. A 30 minute penetrant dwell time provided a sufficient penetration time without drying or causing excessive background fluorescence. To remove the penetrant from the surface of the part, an emulsifier is necessary. Both lipophilic (oil-based) and hydrophilic (water-based) emulsifiers were tested using various dwell times to determine which emulsifier provided the most effective penetrant removal without overwashing the part. In the case of hydrophilic emulsifiers, the concentration was also varied. The conclusion was that Magnaflux ZR10, a hydrophilic emulisfier, at 33% concentration with a 2 minute dwell time provided optimum conditions for excess penetrant removal. Dry developer and water soluble wet developer were compared as well. The wet developer seemed to result in higher sensitivity and reliability with an 8 to 10 minute dwell time prior to inspection. The results of "Methods Improvement of the Fluorescent Penetrant Inspection (FPI) Process" are summarized in Table 1.

B. OBJECTIVE

The overall objective of this program was to determine statisically whether or not the proposed improvements suggested in "Methods Improvement" actually provided increased sensitivity and reliability over the current methods being used in the overhaul facilities of the ALC. The objective of Phase I of this program was to flaw 51 specimens in 3 predetermined flaw size categories, perform a baseline laboratory inspection, and demonstrate current FPI capability using a small hand processing line at San Antonio Air Logistics Center (SA-ALC), Kelly AFB, TX. The objective of Phase II of this program included a demonstration at SA-ALC of FPI capability using modifications and improvements, and the estimation of a probability of detection (POD) curve for both the Phase I (baseline) demonstration and the Phase II (improved and modified methods) demonstration. Phase III included the statistical comparison of the data resulting from the baseline, improved surface preparations, and modified process parameters as well as the metallurgical cut-up of twenty fatigue-cracked specimens to determine the aspect ratio of the cracks. A flow chart of the program is shown in Figure 3.

Surface After Vapor Blasting
(Shows Uniform Deformation of Metal Surface)



Surface After Grit Blasting
(Shows Uneven and Deeper Deformation of Metal Surface)

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Figure 2. Effects of Vapor Blasting and Grit Blasting on Inconel 718 Polished Surface (Cross-Sectional View of Sample)

TABLE 1. MODIFIED FPI PROCESS PROCEDURES SUGGESTED IN "METHODS IMPROVEMENT"

1.	Surface Preparation Procedures (on contaminated specimens)	
	Inconel 718	Vapor degrease, carbon remover soak (PC-111) at 130 to 140°F (54 to 60°C), hot water rinse (two times), light vapor blast, vapor degrease (Ref 2), or chem-mil with No. 9B solution at 130°F for 2 minutes.
	Ti-6Al-4V	Soak specimens in alkaline rust remover at 180 to 190°F (82 to 88°C) for 5 minutes, light vapor blast (Ref 3), chem-mill with nitric-hydrofluoric chem-mill solution at room temperature for 3 minutes.
2.	Penetrant Group VI* Magnaflux ZL-30	30 minute dwell
3.	Emulsifier Group VI* Magnaflux ZR-10A hydrophilic emulsifier	2 minute dwell
4.	Rinse in water	
5.	Wet Developer Group VI* 8 oz/gal (14.09 g/l) Magnaflux ZP-13A	8-10 minute dwell
6.	Dry in Hot Oven	

*All group classification to MIL-I-25135C

C. SCOPE

The technical effort of this program included fatigue cracking 51 AFWAL supplied specimens and placing them in 3 flaw size categories with an equal number of specimens in each. The specimens were then inspected in the laboratory to determine a baseline for the size and intensity of the FPI indications prior to further processing. The specimens were contaminated and cleaned according to state-of-the-art methods and processed for inspection according to state-of-the-art ALC methods. The data was then analyzed to determine if a statistically significant difference existed between the baseline inspection and either of the modified inspections. The baseline processing consists of state-of-the-art ALC procedures (see References 2 and 3) which includes chemical cleaning procedures as well as a vapor blast to remove contamination. The processing parameters include lipophilic emulsifier and dry developer. After inspection, the specimens were reprocessed using the improved methods (improved surface preparation followed by modified process parameters) and reinspected, resulting in a total of 3 complete inspections. Each specimen was inspected by five independent inspectors. A POD plot was then generated for each inspection program. Subsequently, the data was analyzed to determine which of the investigated statistical models applied. The data was then analyzed to determine if a statistically significant difference existed between the baseline inspection and either of the modified inspections in the areas of detectability, intensity, and type II errors (false calls). Twenty fatigue cracked specimens were broken open to estimate the aspect ratio.

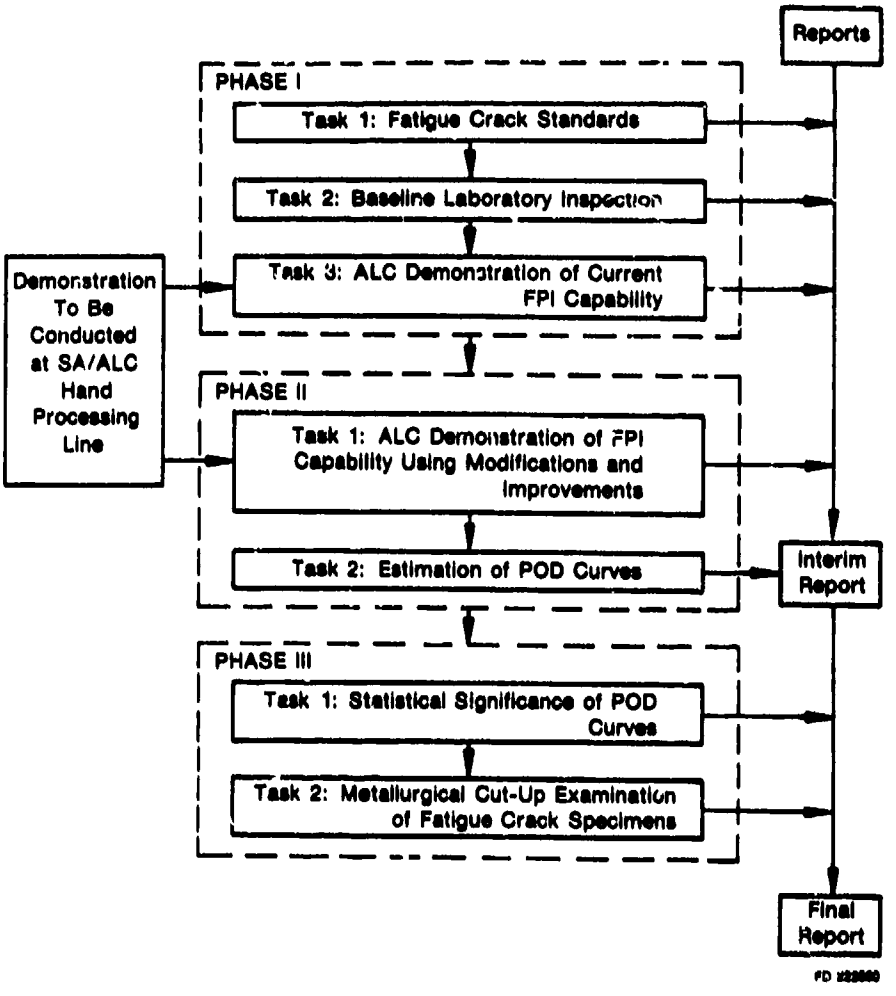


Figure 3. Program Flow Chart

D. PROGRAM APPROACH

To demonstrate the difference between the baseline and improved methods, a baseline demonstration using current state-of-the-art surface preparation and process parameters was first performed. Subsequently, the improved surface preparation procedures were applied while using the state-of-the-art FPI process parameters. This allowed a direct comparison of the improved surface preparation procedures with state-of-the-art surface preparation procedures. The subsequent demonstration employed improved process parameters after the improved surface preparation procedures had already been used. The result is an inspection using a completely improved process which can be compared to the baseline to show the total improvement and to the improved surface preparations to show the improvement resulting from modified process parameters.

To keep the demonstrations valid, approximately the same number of uncracked or dummy specimens as cracked specimens were used. The dummy specimens played a dual role; they not only prevented the inspectors from seeing a crack in every specimen regardless of whether or not an indication actually existed, but also provided a way to help determine the number of false calls present. In "Methods Improvement," it was noted that often a false call

happened to be close to the actual crack, resulting in the inspection being scored as a true indication. The number of indications recorded on such an inspection sheet made it obvious that an indication could hardly help from being recorded near the actual crack. The dummy specimens should give some indication of how many false calls are being recorded. After the data was plotted, a statistical approach was selected. First, the distribution of the data was considered in order to have a valid model for this particular set of data. Too often statistical models are applied to analyze a set of data without first considering how the data actually behaves and what the physical factors are which influence the parameter of interest. The model is sometimes chosen because it is easy to use or because it is well known. The results of this kind of approach to data analysis are often misleading. After the statistical approach was chosen, the most pertinent parameters leading to a successful inspection were statistically analyzed to evaluate the modifications. The parameters chosen were detectability, indication intensity, and Type II errors (false calls). Twenty fatigue cracked specimens were broken open to estimate the aspect ratio of the flaws in order to determine if a correlation exists between crack length, crack depth, and detectability.

SECTION II

TECHNICAL PROGRESS

A. SUMMARY OF WORK ACCOMPLISHED

Phase I provided for the fatigue cracking of 51 AFWAL furnished specimens of Ti-6Al-4V and Inconel 718. Both of these alloys are commonly used in aircraft engines and were used in "Methods Improvement." This phase also allowed an initial laboratory baseline inspection and a demonstration of current ALC FPI capability.

The Air Force provided two sizes of Ti-6Al-4V blades (7.62 cm (3 in) and 12.7 cm (5 in)) and Inconel 718 and Ti-6A1-4V bars, 0.635 by 2.54 by 15.24 cm (¼ by 1 by 6 in)). The technical effort of Phase I is summarized below:

1. The fatigue cracked specimens were prepared and crack lengths documented by P&WA/GPD. The cracked and uncracked specimens were identically prepared.

2. A baseline laboratory inspection was performed to document the FPI indications prior to testing.

3. The specimens were exposed to simulated engine contamination and cleaned according to state-of-the-art cleaning procedures prior to inspection.

4. The specimens were processed according to current state-of-the-art process parameters outlined in Table 2 and then inspected by five independent inspectors at a small hand processing line at SA-ALC.

5. The data was tabulated and a POD plot was estimated.

Phase II provided for the demonstration of improvements and modifications at the ALC and the generation of a POD curve from the resulting data. The technical effort is outlined below:

1. The specimens were exposed to the surface preparation procedures suggested in "Methods Improvement" and described in Table 3. The specimens were processed with state-of-the-art processing parameters and then inspected by five independent inspectors at a small hand processing line at SA-ALC.

2. The specimens were processed with modified processing parameters (Table 4) and inspected again by five independent inspectors at a small hand processing line at SA-ALC.

3. POD plots were estimated from the data gathered in this Phase.

TABLE 2. BASELINE DEMONSTRATION PARAMETERS

1.	Surface Preparation Procedures* (on contaminated specimens)	
	Inconel 718	Vapor degrease, carbon remover soak (PC-111) at 130 to 140°F (54 to 60°C), hot water rinse (two times), light vapor blast, vapor degrease (Ref 2).
	Ti-6Al-4V	Soak specimens in alkaline rust remover at 180 to 190°F (82 to 88°C) for 5 minutes, light vapor blast (Ref 3).
2.	Penetrant Group VI** Magnaflux ZL-30	30 minute dwell
3.	Emulsifier Group VI** Magnaflux ZE-4A lipophilic emulsifier	1-½ minute dwell
4.	Rinse in water	
5.	Dry in hot oven	
6.	Dry Developer Group VI** Magnaflux ZP-4B	8-10 minutes

*Baseline surface preparation parameters are those defined in USAF T.O. 2J-TF39-3 and NAVAIR 02-1-517/T.O. 2-1-111/DMWR 55-2800-206
**All group classification to MIL-I-25135C.

TABLE 3. IMPROVED SURFACE PREPARATION DEMONSTRATION PARAMETERS

1.	Surface Preparation Procedures	
	Inconel 718	Vapor blasting and chemical milling with No. 9B solution at 130°F for 2 min.**
	Ti-6Al-4V	Vapor blasting and chemical milling with nitric hydrofluoric solution at room temperature for 3 min.**
2.	Penetrant* Magnaflux ZL-30	30 minute dwell
3.	Emulsifier* Magnaflux ZE-4A lipophilic emulsifier	1-½ minute dwell
4.	Rinse in water	
5.	Dry in hot oven	
6.	Dry Developer Magnaflux ZP-4B	8-10 min dwell

*Group VI: (All group classifications to MIL-I-25135C)
**See Table 7 page 24

TABLE 4. IMPROVED SURFACE PREPARATION AND PROCESS VARIABLES DEMONSTRATION PARAMETERS

1.	Penetrant* Magnaflux ZL-30	30 min dwell
2.	Emulsifier* (33% concentration Magnaflux ZR-10A hydrophilic emulsifier)	2 min dwell
3.	Rinse in water	
4.	Wet developer* 8 oz/gal (14.09 g/l) Magnaflux ZP-13A	8-10 min dwell
5.	Dry in hot oven	

*Group VI: (All group classifications to MIL-I-25135C)

NOTE: Specimens were chem-milled for improved surface preparation demonstration. Phase II demonstration was conducted after improved surface preparation demonstration.

Phase III provided for the statistical comparison of the modifications and improvements both to each other and to the baseline procedure. In addition, twenty of the fatigue cracked specimens were to be broken open to estimate the aspect ratio. The technical progress is:

1. Data was analyzed to determine which variables are related to detectability and what type of distribution, if any, is applicable.

2. Data from each run was compared to determine if a statistically significant difference could be found in detectability or brightness.

3. False calls (Type II errors) for each method were statistically compared.

4. A total of 20 fatigue cracked specimens were opened to estimate the aspect ratios.

B. RESULTS

1. Phase I

a. Fatigue Cracking and Documentation

Fifty-one (51) Ti-6A1-4V blades and bars, as well as Inconel 718 bars were fatigue cracked. The 20 bar specimens from the "Methods Improvements" program were transferred for use in this program. The remaining specimens needed to fill out the flaw size categories of 0.2 cm to 0.25 cm (0.080 in to 0.100 in), 0.25 cm to 0.508 cm (0.100 in to 0.200 in) and 0.508 cm to 0.76 cm (0.200 in to 0.300 in) with 17 specimens in each category, were fatigue cracked by P&WA/GPD. Crack lengths were documented with acetate film replication. In the fatigue crack specimen documentation, the crack locations were measured from the identification marked end of the specimen to the flaw (Figure 4). The same method was used on both the top and bottom surface. The results of crack documentation are shown in Table 5. Typical replica photographs are shown in Figures 5 and 6.

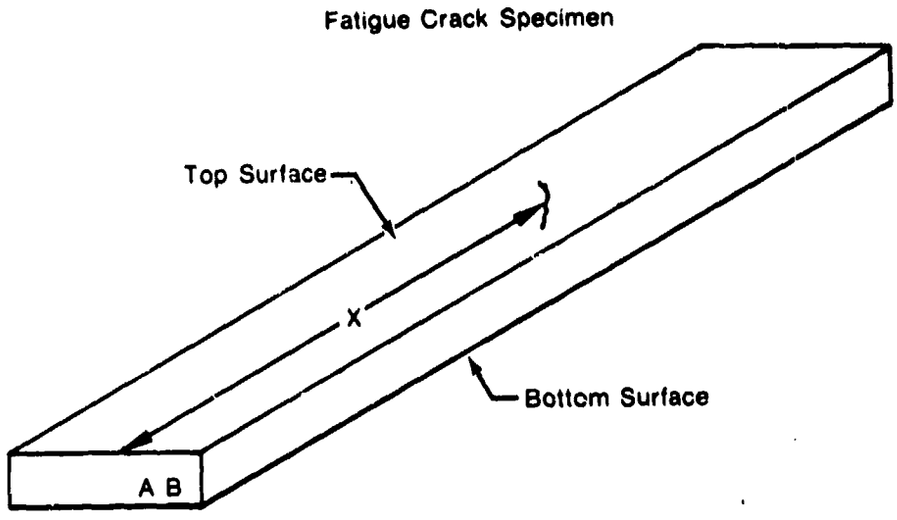


Figure 4. Sketch of Fatigue Crack Specimen

After the necessary number of specimens in each flaw size category were obtained, all of the bar specimens (cracked and uncracked) were given an identical surface finish to eliminate any identifying marks.

A baseline laboratory inspection was performed prior to any of the surface preparation procedures in order to document the size and intensity of the indications in the initial state. The modified process parameters were used to obtain this data.

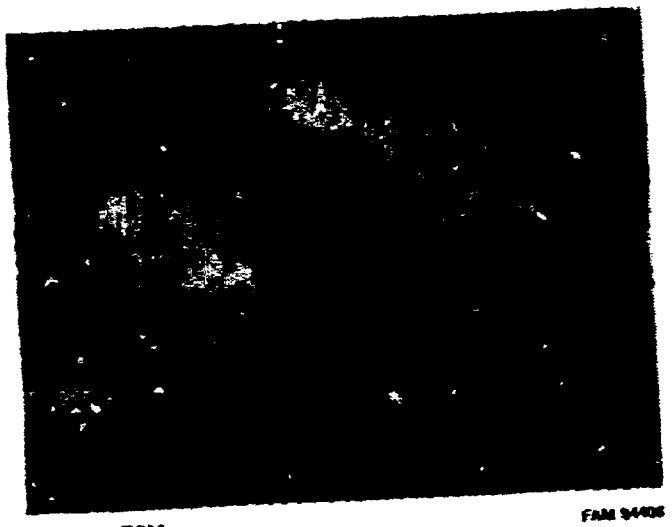
The baseline data should allow a determination of the effectiveness of the improved methods in returning a part to its original as-cracked state.

b. Contamination and Cleaning

The specimens were exposed to simulated engine contamination by being heated in aircraft engine lubricant (PWA specification 521, MIL-L-7808) and exposed to the fumes while being thermally cycled from room temperature to 315°C (600°F). The surface contamination is thorough though not possibly the worst that would be encountered during engine overhaul: it thoroughly covered the surfaces of the specimens, including the cracks but was not baked at the highest temperatures seen in the engine for an extended period of time as the engine sees.

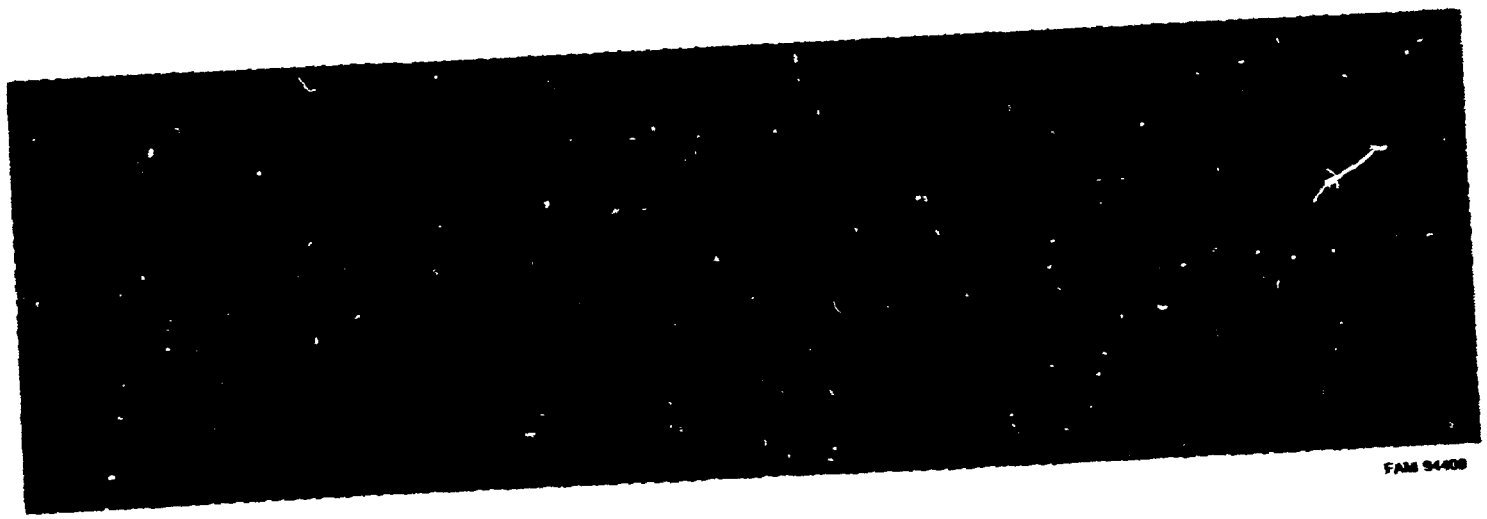
TABLE 5. FLAWED SPECIMENS

Specimen Number	Flaw Size (By Replica) (cm)	(in.)	Location	Type of Specimen
0.20 cm-0.25 cm (0.080"-0.100")				
77	0.239	0.094	Convex center 0.476 cm (3/16") from root	Large Ti Blade
81	0.254	0.100	Both sides trailing edge 2.54 cm (1") from root	Large Ti Blade
87	0.152	0.060	Both sides trailing edge 1.27 cm (1/2") from root	Large Ti Blade
99	0.244	0.096	Both sides trailing edge 2.23 cm (7/8") from root	Large Ti Blade
153	0.211	0.083	Convex center 0.318 cm (1/8") from root	Small Ti Blade
165	0.229	0.090	Convex center 0.635 cm (1/4") from root	Small Ti Blade
170	0.236	0.093	Convex center 0.318 cm (1/8") from root	Small Ti Blade
53	0.216	0.085	6.7 cm (2.67") Bottom	Ti Bar
23	0.241	0.095	9.27 cm (3.65") Bottom	Ti Bar
15	0.203	0.080	8.36 cm (3.29") Top	Inconel Bar
16	0.203	0.080	6.68 cm (2.63") Top	Inconel Bar
74	0.251	0.099	6.76 cm (2.66") Bottom	Inconel Bar
102	0.198	0.078	8.64 cm (3.40") Bottom	Inconel Bar
201	0.244	0.096	8.13 cm (3.20") Top	Inconel Bar
207	0.254	0.100	6.88 cm (2.71") Bottom	Inconel Bar
218	0.249	0.098	8.76 cm (3.45") Top	Inconel Bar
219	0.229	0.090	8.26 cm (3.25") Top	Inconel Bar
0.25 cm-0.51 cm (0.100"-0.200")				
72	0.452	0.178	Both sides trailing edge 2.06 cm (13/16") from tip	Large Ti Blade
76	0.478	0.188	Both sides trailing edge 1.27 cm (1/2") from root	Large Ti Blade
79	0.401	0.158	Both sides trailing edge 1.27 cm (1/2") from root	Large Ti Blade
86	0.381	0.150	Trailing edge both sides 2.54 cm (1") from root	Large Ti Blade
92	0.259	0.102	Convex center near root	Large Ti Blade
94	0.465	0.183	Both sides trailing edge 1.27 cm (1/2") from root	Large Ti Blade
118	0.315	0.124	Both sides trailing edge	Small Ti Blade
121	0.277	0.109	Convex center 0.318 cm (1/8") from root	Small Ti Blade
34	0.338	0.133	6.30 cm (2.48") Bottom	Inconel Bar
79	0.257	0.101	8.58 cm (3.38") Top	Inconel Bar
91	0.343	0.135	6.68 cm (2.63" Bottom	Inconel Bar
195	0.401	0.158	6.86 cm (2.70") Top	Inconel Bar
197	0.457	0.180	7.44 cm (2.93") Bottom	Inconel Bar
202	0.305	0.120	8.09 cm (3.187") Bottom	Inconel Bar
203	0.460	0.181	7.52 cm (2.96") Bottom	Inconel Bar
214	0.472	0.186	6.81 cm (2.68") Top	Inconel Bar
221	0.368	0.145	6.81 cm (2.68") Top	Inconel Bar
0.5 cm-0.76 cm (0.200"-0.300")				
59	0.533	0.210	Convex center near root	Large Ti Blade
63	0.584	0.230	Convex center 0.318 cm (1/8") from root	Large Ti Blade
101	0.554	0.218	Both sides trailing edge 0.953 cm (3/8") from root	Small Ti Blade
128	0.757	0.298	Convex center 0.318 cm (1/8") from root	Small Ti Blade
145	0.724	0.285	Convex center near root	Small Ti Blade
150	0.572	0.225	Convex center 0.318 cm (1/8") from root	Small Ti Blade
158	0.615	0.242	Convex center 0.953 cm (3/8") from root	Small Ti Blade
164	0.516	0.203	Both sides trailing edge 0.953 cm (3/8") from root	Small Ti Blade
169	0.503	0.198	Convex center 0.318 cm (1/8") from root	Small Ti Blade
183	0.516	0.203	Convex center 0.318 cm (1/8") from root	Small Ti Blade
227	0.630	0.248	7.39 cm (2.91") Top	Inconel Bar
242	0.737	0.290	7.49 cm (2.95") Bottom	Inconel Bar
238	0.716	0.282	6.50 cm (2.56") Top	Inconel Bar
225	0.696	0.274	6.27 cm (2.47") Bottom	Inconel Bar
38	0.800	0.315	8.00 cm (3.15") Bottom	Inconel Bar
43	0.820	0.323	8.22 cm (3.24") Bottom	Inconel Bar
52	0.521	0.205	9.19 cm (3.62") Bottom	Inconel Bar



Mag: 50X

Figure 5. Fatigue Crack in Inconel 718 Bar Specimen No. 221



Mag: 100X

Figure 6. Fatigue Crack in Ti-Al-4V Blade

The specimens were then subjected to state-of-the-art chemical cleaning procedures. As found previously, the chemical cleaning did not remove all of the surface contamination. In many instances, areas of thick, baked-on contamination remained which would certainly trap penetrant and, if in the proper location, could completely obscure the largest crack present in the specimen set (See Figures 7, 8 and 9). As a result, the vapor blast operation performed in "Methods Improvement" was necessary on this specimen set also. The vapor blast operation was a light vapor blast performed at a standoff distance of 40.6 to 45.7 cm (16 to 18 in.) at 6.8×10^5 Pa (100 psi) for 30 seconds. This procedure was adequate to remove the contamination without removing excess parent material. Vapor blasting has previously resulted in a nearly uniform surface condition whereas grit blasting causes large surface irregularities which may trap penetrant and cause excess background fluorescence. Vapor blasting will, however, cause some smear metal depending on the amount of time spent in a particular location, blast pressure, and the distance of the nozzle from the part.

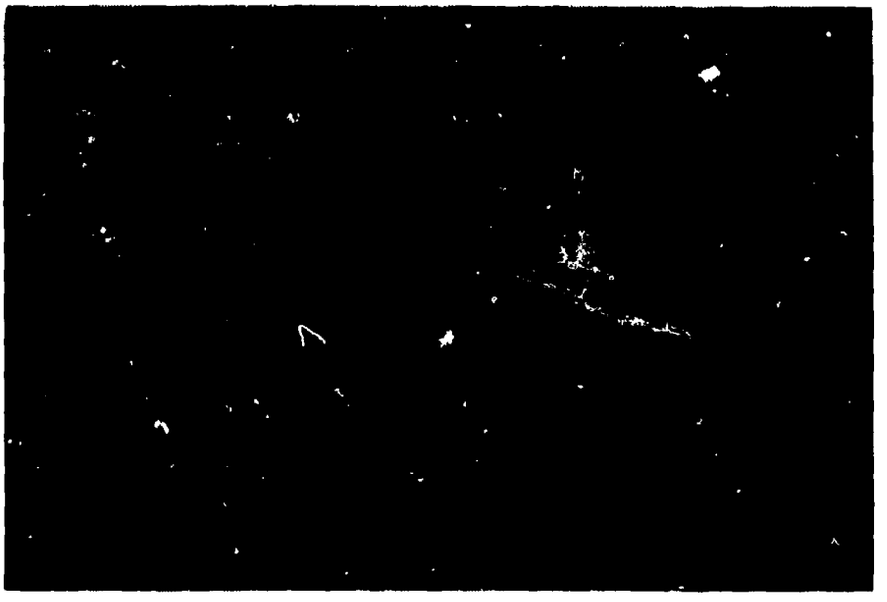


Figure 7. Inconel 718 Bar Specimen After Contamination and State-of-the-Art Chemical Cleaning Procedures

The specimens were taken to Kelly Air Force Base, San Antonio, Texas for penetrant processing at a small, hand processing line. After the parts were thoroughly cleaned, they were processed according to state-of-the-art procedures. Each specimen was inspected by five independent inspections provided by Electrix Equipment Inc., an independent subcontractor. State-of-the-art FPI processing parameters include ZL-30 penetrant, lipophilic emulsifier, and dry developer. In order to keep the time to a minimum from full development until the last inspector had seen the part, yet still process a reasonable number of parts at one time, the specimens were processed in lots of approximately six. The results of each inspection were recorded by the inspector on a sketch of the component as shown in Figures 10 through 12. Partitions separated the inspectors thus ensuring independent inspections. The inspectors were instructed only to mark indications as accurately as they could on the sketch with respect to length and location, and to indicate the relative brightness of each indication as bright, medium, or dim. The results of this inspection are shown in Table 6 and the estimate of the POD curve is shown in Figure 13.

Figure 8. Edge of Inconel 718 Bar Specimen After Contamination and State-of-the-Art Chemical Cleaning Procedures

Figure 9. Titanium 6Al-4V Blade After Contamination and State-of-the-Art Chemical Cleaning Proceaures

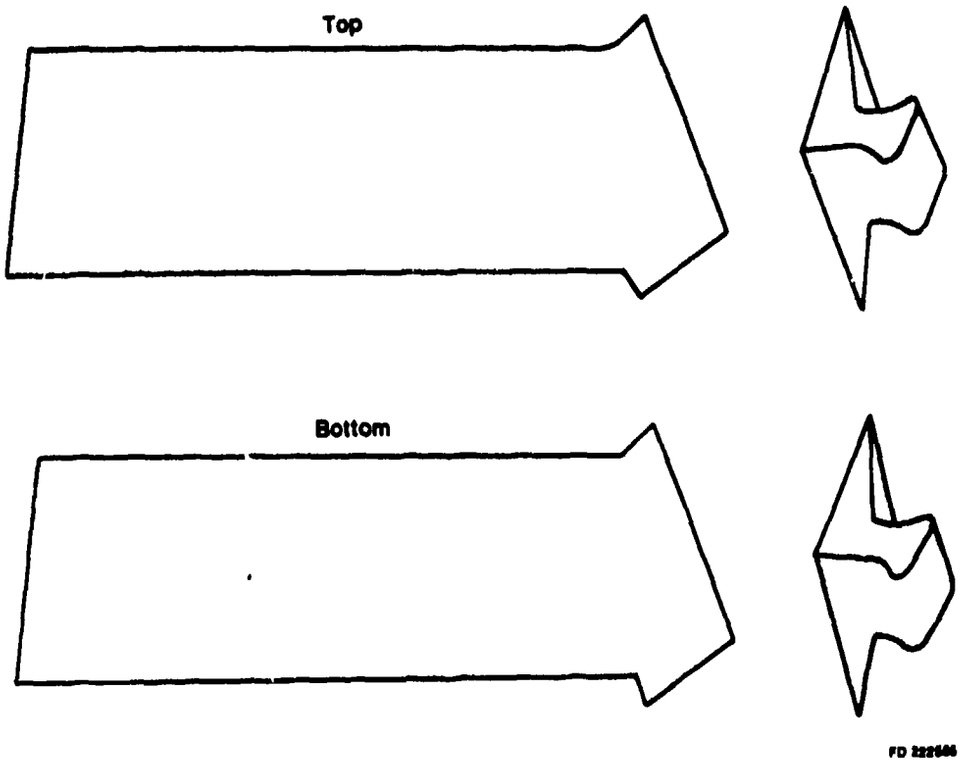


Figure 10. Large Titanium Blade Inspection Sheet

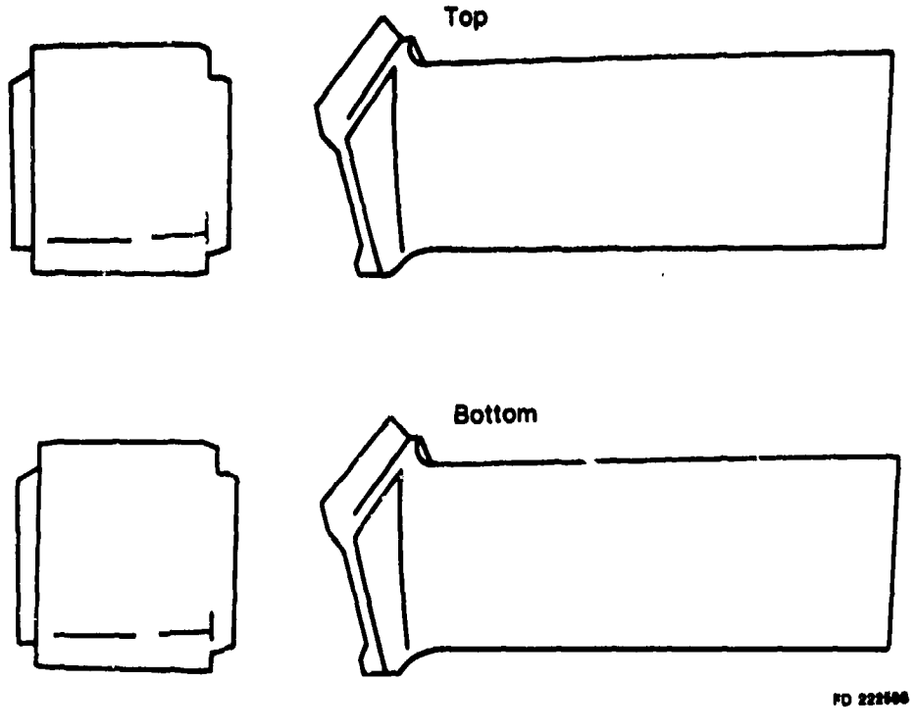


Figure 11. Small Titanium Blade Inspection Sheet

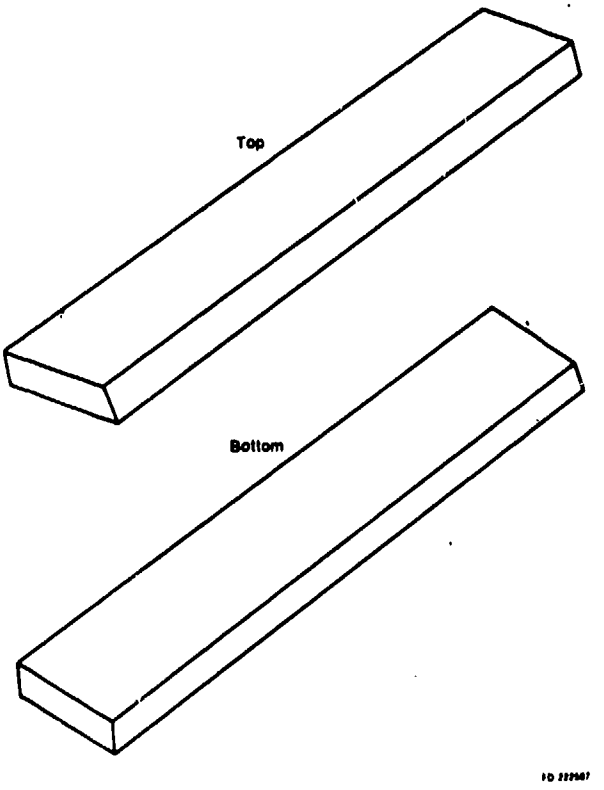


Figure 12. Inconel Bar Inspection Sheet

TABLE 6. BASELINE INSPECTION OF FLAWED SPECIMENS

Specimen Number	Flaw Size (By Replica) (cm)	(in.)	Material	Indications Found Bright	Medium	Dim	Ratio[1]
0.20 cm-0.25 cm (0.080"-0.100")							
77	0.239	0.094	Ti	4	1	0	5/5
81	0.254	0.100	Ti	0	1	0	1/5
87	0.152	0.060	Ti	0	0	0	0/5
99	0.244	0.096	Ti	0	1	0	1/5
153	0.211	0.083	Ti	4	1	0	5/5
165	0.229	0.090	Ti	0	0	0	0/5
170	0.236	0.093	Ti	3	2	0	5/5
53	0.216	0.085	Ti	0	0	0	0/5
23	0.241	0.095	Ti	0	0	0	0/5
15	0.203	0.080	In	0	0	0	0/5
16	0.203	0.080	In	0	0	0	0/5
74	0.251	0.099	In	0	0	0	0/5
102	0.198	0.078	In	0	0	0	0/5
201	0.244	0.096	In	0	0	0	0/5
207	0.254	0.100	In	0	0	0	0/5
218	0.249	0.098	In	0	1	0	0/5
219	0.229	0.090	In	0	0	0	0/5
0.25 cm-0.51 cm (0.100"-0.200")							
72	0.452	0.178	Ti	0	0	0	0/5
76	0.478	0.188	Ti	3	2	0	5/5
79	0.401	0.158	Ti	5	0	0	5/5
86	0.381	0.150	Ti	0	0	0	0/5
92	0.259	0.102	Ti	5	0	0	5/5
94	0.465	0.183	Ti	5	0	0	5/5
118	0.315	0.124	Ti	4	1	0	5/5
121	0.277	0.109	Ti	0	0	0	0/5
34	0.338	0.133	In	0	0	0	0/5
79	0.257	0.101	In	0	0	0	0/5
91	0.343	0.135	In	0	0	0	0/5
195	0.401	0.158	In	0	0	0	0/5
197	0.457	0.180	In	4	1	0	5/5
202	0.305	0.120	In	0	0	0	0/5
203	0.460	0.181	In	0	0	0	0/5
214	0.472	0.186	In	0	0	0	0/5
221	0.368	0.145	In	0	0	0	0/5
0.51 cm-0.76 cm (0.200"-0.300")							
59	0.533	0.210	Ti	0	0	0	0/5
63	0.584	0.230	Ti	1	3	0	4/5
101	0.554	0.218	Ti	3	0	0	3/5
128	0.757	0.298	Ti	5	0	0	5/5
145	0.724	0.285	Ti	0	0	0	0/5
150	0.572	0.225	Ti	5	0	0	5/5
158	0.615	0.242	Ti	0	1	1	2/5
164	0.516	0.203	Ti	3	1	1	5/5
169	0.503	0.198	Ti	5	0	0	5/5
183	0.516	0.203	Ti	5	0	0	5/5
227	0.630	0.248	In	0	0	0	0/5
242	0.737	0.290	In	0	0	0	0/5
238	0.716	0.282	In	0	0	0	0/5
225	0.696	0.274	In	0	0	0	0/5
38	0.800	0.315	In	0	0	0	0/5
43	0.820	0.323	In	0	0	0	0/5
52	0.521	0.205	In	0	0	0	0/5

[1]Total found/Inspection opportunities.

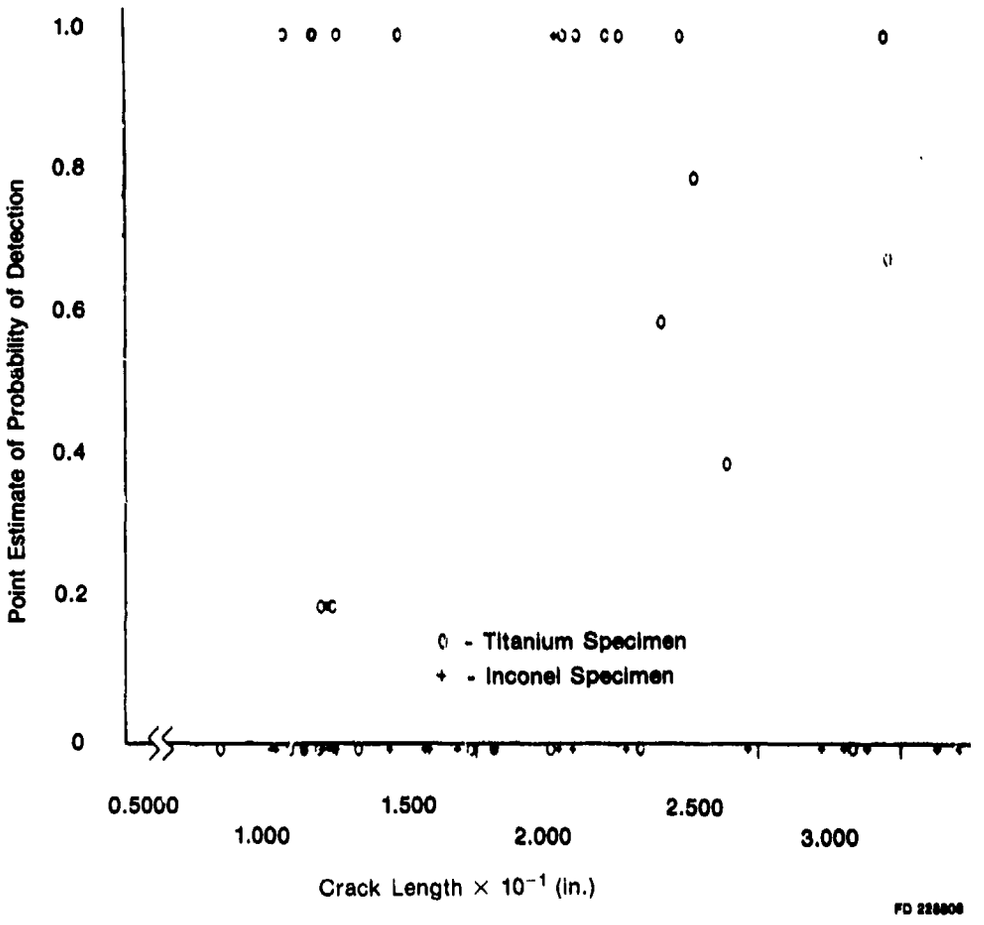


Figure 13. Point Estimates of Probability of Detection for the Baseline Inspections

2. Phase II

After the specimens were inspected in Phase I, they were ultrasonically cleaned in methyl ethyl ketone (MEK) to remove entrapped penetrant from the fatigue cracks. They were then chem-milled in the solutions shown in Table 7 at the time and temperature parameters shown in Table 1. The chem-milling operation is designed to evenly remove metal without any selective attack such as intergranular attack (IGA) common to many etches used in metallography. The even metal removal is used to remove smear metal from crack openings and thus allow the penetrant to enter and expose the cracks. The chem-mill operation can be used not only to remove smear metal resulting from a vapor blast operation, but also to remove smear metal resulting from a rub condition, which can be encountered in a broach slot region, for example. On polished specimens, the chemical milling procedure removes approximately 0.00254 mm to 0.00381 mm (0.00010" to 0.00015") of material on Inconel 718 and Ti-6Al-4V. This small amount of metal removal seems to be adequate to remove the smear metal generated by a light vapor blast. The amount of material removed should be compatible with the dimensional standards of the engine components. For components the closest to their dimensional limits likely to be seen, several overhauls could be performed. For a nominal component, the LCF life would be exceeded by several overhauls before the closest dimensional tolerence is exceeded.

TABLE 7. CHEMICAL MILL COMPOSITIONS

Ti-6Al-4V Chemical Mill:

HNO_3	HF	H_2O	Temperature
35%	3.5%	61.5%	Room Temperature

Inconel 718 Chemical Mill:

Solution No. 9B

HCl	HNO_3	H_2O	$FeCl_3$	$CaSO_4$	Temperature
45%	5%	50%	20 g/gal (5.28 g/l)	36 g/gal (9.51 g/l)	130°F (54.4°C)

The FPI process parameters used for this particular inspection were the same as those used in the baseline so the results of improved surface preparation could be examined independently of improved process parameters. The inspections were performed in the same manner as in the baseline demonstration. The data is tabulated in Table 8 and the POD curve is plotted in Figure 14. Improved surface preparation procedures seem to show increased detectability from baseline according to Figure 14.

The specimens were again ultrasonically cleaned and reprocessed using the improved process parameters. In "Methods Improvement," the improved process parameters resulted in brighter indications and less background fluorescence. Results from the latest study (see Table 9 and Figure 15) show little difference in detectability from the state-of-the-art process parameters to the improved process parameters, but a large difference in the intensity of the indications seems apparent. Table 10 compares the difference in intensity between the two improvement phases. The data indicates that 23 of the 51 flawed specimens showed increased brightness while only 2 specimens showed a decrease in intensity. One flaw was detected only after all modifications were made. Table 11 illustrates the ability of the surface preparation procedures to return the specimens to their original as-cracked condition after contamination. The data indicate that only 8 specimens out of 51 were not returned to their original state of detectability. The data indicates that the improved process parameters increased the intensity of the indications. This may result from a cleaner wash with the hydrophilic emulsifier and better development resulting from the use of wet developer. It should be noted, however, that for relatively large flaw sizes, as encountered in this program, the improved intensity only makes the indications easier to see, but for small flaw sizes, an increase in intensity from dim to medium may well mean the difference between passing over a flaw and detecting it.

PHASE III

After the inspections were completed and the data tabulated, the task of analyzing the data and breaking open a sample (20 specimens) of the cracked population to determine aspect ratio was begun. The data analysis is crucial for drawing conclusions from the data so the effects of the modifications can be assessed.

TABLE 8. IMPROVED SURFACE PREPARATION INSPECTION RESULTS (FLAWED SPECIMENS)

Specimen Number	Flaw Size (By Replica) (cm)	(in.)	Material	Indications Found: Bright	Medium	Dim	Ratio[1]
0.20 cm-0.25 cm (0.080"-0.100")							
77	0.239	0.094	Ti	5	0	0	5/5
81	0.254	0.100	Ti	5	0	0	5/5
87	0.152	0.060	Ti	5	0	0	5/5
99	0.244	0.096	Ti	0	3	0	3/5
153	0.211	0.083	Ti	5	0	0	5/5
165	0.229	0.090	Ti	1	4	0	5/5
170	0.236	0.093	Ti	2	3	0	5/5
53	0.216	0.085	Ti	5	0	0	5/5
23	0.241	0.095	Ti	0	0	0	0/5
15	0.203	0.080	In	0	0	0	0/5
16	0.203	0.080	In	0	0	0	0/5
74	0.251	0.099	In	0	0	0	0/5
102	0.198	0.078	In	0	0	3	3/5
201	0.244	0.096	In	3	1	1	5/5
207	0.254	0.100	In	0	0	0	0/5
218	0.249	0.098	In	0	3	2	5/5
219	0.229	0.090	In	0	0	0	0/5
0.25 cm-0.51 cm (0.100"-0.200")							
72	0.452	0.178	Ti	5	0	0	5/5
76	0.478	0.188	Ti	0	0	3	3/5
79	0.401	0.158	Ti	1	3	0	4/5
86	0.381	0.150	Ti	0	0	0	0/5
92	0.259	0.102	Ti	5	0	0	5/5
94	0.465	0.183	Ti	5	0	0	5/5
118	0.315	0.124	Ti	3	2	0	5/5
121	0.277	0.109	Ti	0	1	4	5/5
34	0.338	0.133	In	0	0	0	0/5
79	0.257	0.101	In	5	0	0	5/5
91	0.343	0.135	In	0	0	0	0/5
195	0.401	0.158	In	1	4	0	5/5
197	0.457	0.180	In	3	2	0	5/5
202	0.305	0.120	In	0	0	0	0/5
263	0.460	0.181	In	3	2	0	5/5
214	0.472	0.186	In	2	2	1	5/5
221	0.368	0.145	In	0	1	4	5/5
0.51 cm-0.76 cm (0.200"-0.300")							
59	0.533	0.210	Ti	0	0	1	1/5
63	0.584	0.230	Ti	5	0	0	5/5
101	0.554	0.218	Ti	0	5	0	5/5
128	0.757	0.298	Ti	1	3	0	4/5
145	0.724	0.285	Ti	0	0	1	1/5
150	0.572	0.225	Ti	5	0	0	5/5
158	0.615	0.242	Ti	4	1	0	5/5
164	0.516	0.203	Ti	3	2	0	5/5
169	0.503	0.198	Ti	5	0	0	5/5
183	0.516	0.203	Ti	4	1	0	5/5
227	0.630	0.248	In	0	0	0	0/5
242	0.737	0.290	In	4	0	0	4/5
238	0.716	0.282	In	5	0	0	5/5
225	0.696	0.274	In	0	5	0	5/5
38	0.800	0.315	In	0	0	0	0/5
43	0.820	0.323	In	5	0	0	5/5
52	0.521	0.205	In	0	0	0	0/5

[1]Total found/Inspection opportunities.

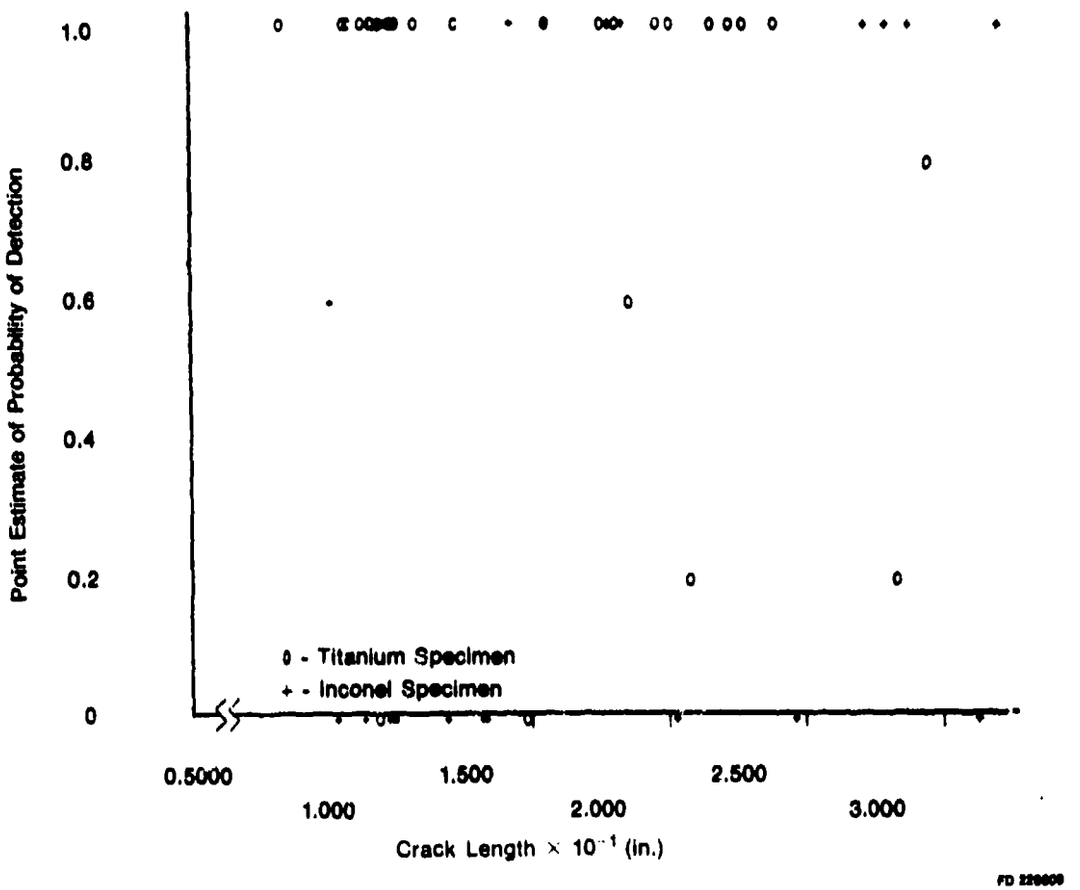


Figure 14. Point Estimates of Probability of Detection for the Improved Surface Preparation Inspect. ns

TABLE 9. IMPROVED SURFACE PREPARATION AND PROCESS PARAMETERS INSPECTION RESULTS (FLAWED SPECIMENS)

Specimen Number	Flaw Size (By Replica) (cm)	(in.)	Material	Indications Found Bright	Medium	Dim	Ratio[1]
0.20 cm-0.25 cm (0.080"-0.100")							
77	0.239	0.094	Ti	5	0	0	5/5
81	0.254	0.100	Ti	4	1	0	5/5
87	0.152	0.060	Ti	4	1	0	5/5
99	0.244	0.096	Ti	2	2	1	5/5
153	0.211	0.083	Ti	5	0	0	5/5
165	0.229	0.090	Ti	5	0	0	5/5
170	0.236	0.093	Ti	5	0	0	5/5
53	0.216	0.085	Ti	5	0	0	5/5
23	0.241	0.095	Ti	0	0	0	0/5
15	0.203	0.080	In	0	0	0	0/5
16	0.203	0.080	In	0	0	0	0/5
74	0.251	0.099	In	0	0	0	0/5
102	0.198	0.078	In	5	0	0	5/5
201	0.244	0.096	In	4	1	0	5/5
207	0.254	0.100	In	0	0	0	0/5
218	0.249	0.098	In	5	0	0	5/5
219	0.229	0.090	In	0	0	0	0/5
0.25 cm-0.51 cm (0.100"-0.200")							
72	0.452	0.178	Ti	5	0	0	5/5
76	0.478	0.188	Ti	3	0	2	5/5
79	0.401	0.158	Ti	5	0	0	5/5
86	0.381	0.150	Ti	0	0	0	0/5
92	0.259	0.102	Ti	5	0	0	5/5
94	0.465	0.183	Ti	5	0	0	5/5
118	0.315	0.124	Ti	5	0	0	5/5
121	0.277	0.109	Ti	4	0	0	4/5
34	0.338	0.133	In	0	0	0	0/5
79	0.257	0.101	In	5	0	0	5/5
91	0.343	0.135	In	0	0	0	0/5
195	0.401	0.158	In	5	0	0	5/5
197	0.457	0.180	In	5	0	0	5/5
202	0.305	0.120	In	0	0	0	0/5
203	0.460	0.181	In	5	0	0	5/5
214	0.472	0.186	In	5	0	0	5/5
221	0.368	0.145	In	5	0	0	5/5
0.51 cm 0.76 cm (0.200" 0.300")							
59	0.533	0.210	Ti	0	1	2	3/5
63	0.584	0.230	Ti	5	0	0	5/5
101	0.554	0.218	Ti	1	4	0	5/5
128	0.757	0.298	Ti	5	0	0	5/5
145	0.724	0.285	Ti	0	0	1	1/5
150	0.572	0.225	Ti	5	0	0	5/5
158	0.615	0.242	Ti	5	0	0	5/5
164	0.516	0.203	Ti	5	0	0	5/5
169	0.503	0.198	Ti	5	0	0	5/5
183	0.516	0.203	Ti	5	0	0	5/5
227	0.630	0.248	In	0	0	0	0/5
242	0.737	0.290	In	5	0	0	5/5
238	0.716	0.282	In	5	0	0	5/5
225	0.696	0.274	In	0	5	0	5/5
38	0.800	0.315	In	0	1	4	5/5
43	0.820	0.323	In	5	0	0	5/5
52	0.521	0.205	In	0	0	0	0/5

[1]Total found/Inspection opportunities.

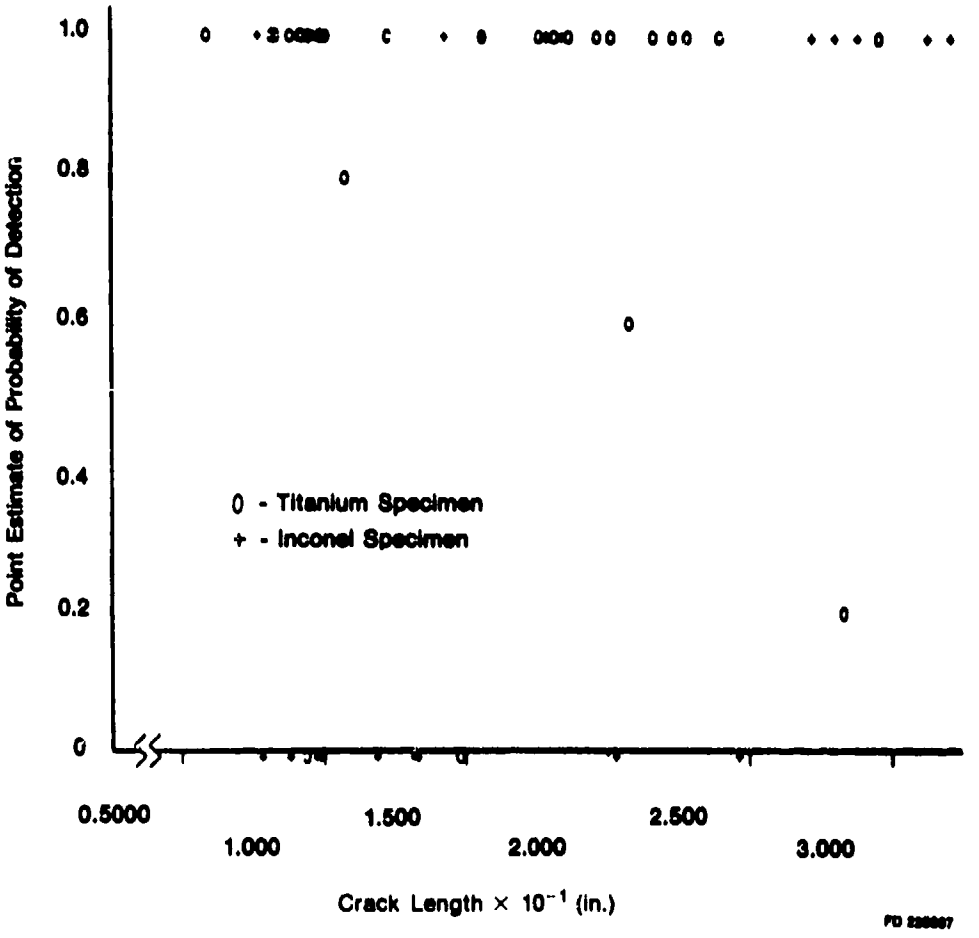


Figure 15. Point Estimates of Probability of Detection for the Improved Surface Preparation and Modified Process Parameters

TABLE 10. COMPARISON OF IMPROVED SURFACE PREPARATIONS (PHASE I) TO IMPROVED SURFACE PREPARATIONS AND PROCESS PARAMETERS (PHASE II) DEMONSTRATIONS

Specimen Number	Flaw Size (By Replica) (cm)	(in.)	Material	Phase I Indications/ Phase II Indications Bright	Medium	Dim
0.20 cm-0.25 cm (0.080"-0.100")						
77	0.239	0.094	Ti	5/5	0/0	0/0
81*	0.254	0.100	Ti	5/4	0/1	0/0
87*	0.152	0.060	Ti	5/4	0/1	0/0
99**	0.244	0.096	Ti	0/2	3/2	0/1
153	0.211	0.083	Ti	5/5	0/0	0/0
165**	0.229	0.090	Ti	1/5	4/0	0/0
170**	0.236	0.093	Ti	2/5	3/0	0/0
53	0.216	0.085	Ti	5/5	0/0	0/0
23	0.241	0.095	Ti	0/0	0/0	0/0
15	0.203	0.080	In	0/0	0/0	0/0
16	0.203	0.080	In	0/0	0/0	0/0
74	0.251	0.099	In	0/0	0/0	0/0
102**	0.198	0.078	In	0/5	0/0	3/0
201**	0.244	0.096	In	3/4	1/1	1/0
207	0.254	0.100	In	0/0	0/0	0/0
218**	0.249	0.098	In	0/5	3/0	2/0
219	0.229	0.090	In	0/0	0/0	0/0
0.25 cm-0.51 cm (0.100"-0.200")						
72	0.452	0.178	Ti	5/5	0/0	0/0
76**	0.478	0.188	Ti	0/3	0/0	3/2
79**	0.401	0.158	Ti	1/5	3/0	0/0
86	0.381	0.150	Ti	0/0	0/0	0/0
92	0.259	0.102	Ti	5/5	0/0	0/0
94	0.465	0.183	Ti	5/5	0/0	0/0
118**	0.315	0.124	Ti	3/5	2/0	0/0
121**	0.277	0.109	Ti	0/4	1/0	4/0
54	0.338	0.133	In	0/0	0/0	0/0
70	0.257	0.101	In	5/5	0/0	0/0
91	0.343	0.135	In	0/0	0/0	0/0
195**	0.401	0.158	In	1/5	4/0	0/0
197**	0.457	0.180	In	3/5	2/0	0/0
202	0.305	0.120	In	0/0	0/0	0/0
203**	0.460	0.181	In	3/5	2/0	0/0
214**	0.472	0.186	In	2/5	2/0	1/0
221**	0.368	0.145	In	0/5	1/0	4/0
0.51 cm-0.76 cm (0.200"-0.300")						
59**	0.533	0.210	Ti	0/0	0/1	1/2
63	0.584	0.230	Ti	5/5	0/0	0/0
101**	0.564	0.218	Ti	0/1	5/4	0/0
128**	0.757	0.298	Ti	1/5	3/0	0/0
145	0.724	0.285	Ti	0/0	0/0	1/1
150	0.572	0.225	Ti	5/5	0/0	0/0
158**	0.615	0.242	Ti	4/5	1/0	0/0
164**	0.516	0.203	Ti	3/5	2/0	0/0
169	0.503	0.198	Ti	5/5	0/0	0/0
183**	0.516	0.203	Ti	4/5	1/0	0/0
227	0.630	0.248	In	0/0	0/0	0/0
242**	0.737	0.290	In	4/5	0/0	0/0
238	0.716	0.282	In	5/5	0/0	0/0
225	0.696	0.274	In	0/0	5/5	0/0
38***	0.800	0.315	In	0/0	0/1	0/4
43	0.820	0.323	In	5/5	0/0	0/0
52	0.521	0.205	In	0/0	0/0	0/0

*Decrease in intensity
**Increase in intensity
***Indication found by Phase II and not by Phase I.

TABLE 11. LABORATORY INSPECTIONS

Specimen Number	Flaw Size (By Replica) (cm)	(in.)	Material	Baseline Laboratory Inspection Brightness	Post Demonstration Laboratory Inspection Brightness
0.20 cm-0.25 cm (0.080"-0.100")					
77	0.239	0.094	Ti	Dim	Bright
81	0.254	0.100	Ti	Bright	Bright
87	0.152	0.060	Ti	Dim	Bright
99	0.244	0.096	Ti	Dim	Bright
153	0.211	0.083	Ti	Bright	Bright
165	0.229	0.090	Ti	Bright	Bright
170	0.236	0.093	Ti	Dim	Bright
53	0.216	0.085	Ti	Bright	Bright
23	0.241	0.095	Ti	No Indication	No Indication
15	0.203	0.080	In	Dim	No Indication
16	0.203	0.080	In	Bright	Bright
74	0.251	0.099	In	Medium	No Indication
102	0.198	0.078	In	Medium	Medium
201	0.244	0.096	In	Medium	Bright
207	0.254	0.100	In	Dim	No Indication
218	0.249	0.098	In	Dim	Medium
219	0.229	0.090	In	Dim	Dim
0.25 cm-0.5 cm (0.100"-0.200")					
72	0.452	0.178	Ti	Dim	Bright
76	0.478	0.188	Ti	Bright	Bright
79	0.401	0.158	Ti	Bright	Bright
86	0.381	0.150	Ti	Dim	No Indication
92	0.259	0.102	Ti	Dim	Bright
94	0.465	0.183	Ti	Bright	Bright
118	0.315	0.124	Ti	Medium	Bright
121	0.277	0.109	Ti	Bright	Medium
34	0.338	0.133	In	No Indication	No Indication
79	0.257	0.101	In	Bright	Bright
91	0.343	0.135	In	Dim	No Indication
195	0.401	0.158	In	Bright	Bright
197	0.457	0.180	In	Bright	Bright
202	0.305	0.120	In	Medium	No Indication
203	0.460	0.181	In	Bright	Bright
214	0.472	0.186	In	Medium	Medium
221	0.368	0.145	In	Bright	Bright
0.51 cm-0.76 cm (0.200"-0.300")					
59	0.533	0.210	Ti	Dim	Medium
63	0.584	0.230	Ti	Dim	Bright
101	0.554	0.218	Ti	Medium	Bright
128	0.757	0.298	Ti	Bright	Bright
145	0.724	0.285	Ti	Medium	No Indication
150	0.572	0.225	Ti	Bright	Bright
158	0.615	0.242	Ti	Medium	Bright
164	0.516	0.203	Ti	Medium	Bright
169	0.503	0.198	Ti	Medium	Bright
183	0.516	0.203	Ti	Bright	Bright
227	0.630	0.248	In	Dim	No Indication
242	0.737	0.290	In	Dim	Bright
238	0.716	0.282	In	Medium	Bright
225	0.696	0.274	In	Bright	Dim
38	0.800	0.315	In	Dim	Dim
43	0.820	0.323	In	Bright	Bright
52	0.521	0.205	In	Dim	No Indication

C. STATISTICAL APPROACH

Several different approaches can normally be taken to evaluate any particular set of nondestructive evaluation data. Each approach has its advantages and disadvantages. So, to determine which approach is correct, the data for the particular experiment must be examined. In many cases a relatively simple technique will yield a valid analysis where a more complicated analysis would not. The most basic approach is the histogram. A histogram provides a simple, easy to understand, graphical presentation of the data. Unfortunately, this technique is imprecise and the data scatter is difficult to quantify. As a result, quantifiable statements concerning data trends and differences between sets of data are difficult to make. A histogram is a good way to quickly discover trends in the data before proceeding with a more time consuming though quantifiable technique. Analytical methods provide the accurate quantification necessary to make strong, supportable statements about data. Of course, the first step in determining which analytical approach to use is to plot the data against pertinent parameters to observe how these parameters influence the appearance of the data. When analyzing nondestructive evaluation data, the parameter most often related to detectability is crack length. Typically, the data will fall into one of the three regions shown in Figure 16. The first region being the range of flaw sizes where, in general, no flaws are being detected as the technique does not have the sensitivity to have significant detectability. The second region is the transition region in which the threshold of detectability occurs. In the final region, the region of high detectability, essentially all of the flaws are being found. It should be noted at this point that other less easily quantifiable factors such as smear metal or flaw tightness can have a similar effect on detectability. The basic model for data which spans all three of these regions is of the form $y = a\,(x)^b$ (see Figure 17). The exponential model has been shown in the past to be a good analytical model for data in the transition and high detectability regions. If the data is solely in the undetectable or high detectability ranges, another model such as a straight line may be appropriate.

Once an analytical model is developed which accurately describes the data, the quantification of the characteristics of the data can be approached. Basically, parametric or nonparametric statistics can be used. Parametric statistics, the family of statistical methods which requires a distribution of the data to be assumed, is commonly employed. A wide variety of mathematically well defined distributions exist. The distributions with attractive characteristics for the evaluation of nondestructive evaluation data are the Gaussian or normal, log normal, and Beta distributions. The Gaussian distribution is very commonly used and, as a result, has the advantage of being familiar to most people. In addition, the computations necessary to determine reliabilities and statistical differences are easily performed and well understood by many. Unfortunately, if the mean of the data in a particular area lies close to a probability of detection of 0 or 1, the assumption of a symmetrical distribution such as this can lead to questionable if not obviously erroneous implications. In order to avoid this situation, a distribution which can compensate for skewing of the data either positively or negatively is needed. Such a distribution is the log normal distribution. Although the log normal distribution will allow for positively skewed data (POD approaching 1) well, it is not effective for negatively skewed data (POD approaching 0). Reliability calculations are not significantly more complex than those for the normal distribution. The Beta distribution will compensate equally well for data at either extreme, but the calculations involved are difficult and time consuming even when a high speed electronic computer is used. For the general case, no distribution is perfect from a standpoint of accurate analysis or practical computation, but the log normal distribution is probably the best overall. As POD approaches 0, an accurate analysis of the upper and lower bounds is of minimal importance since the technique has low reliability as a result of being below its threshold.

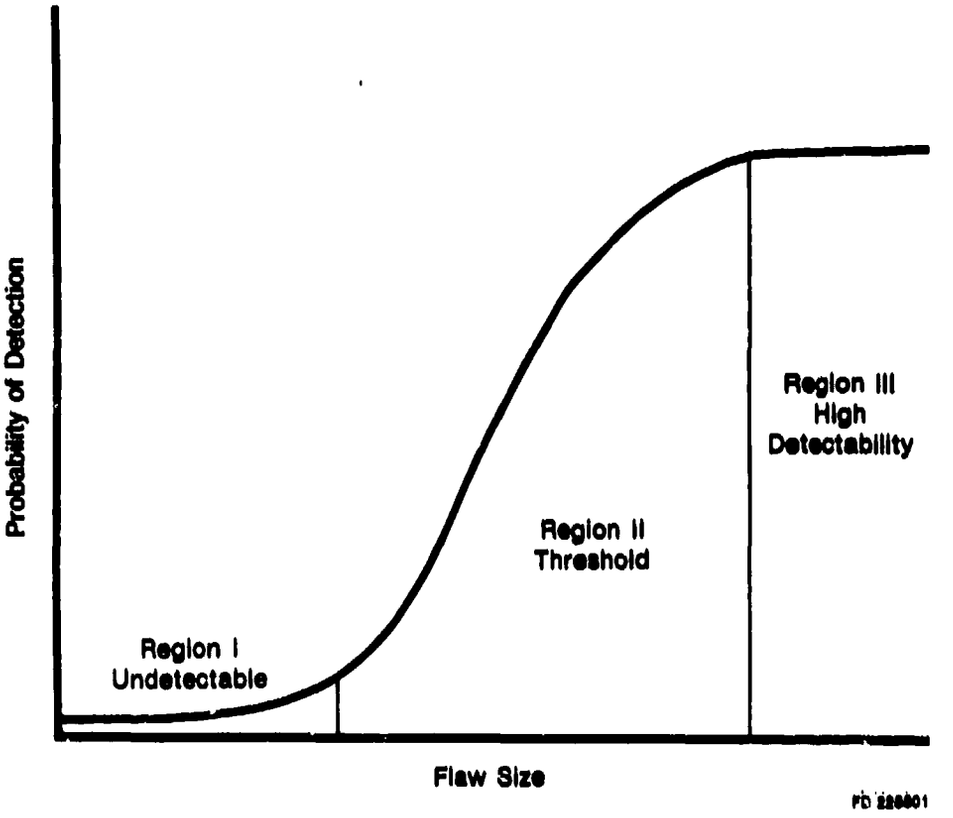


Figure 16. Probability of Detection Versus Flaw Size (Expected)

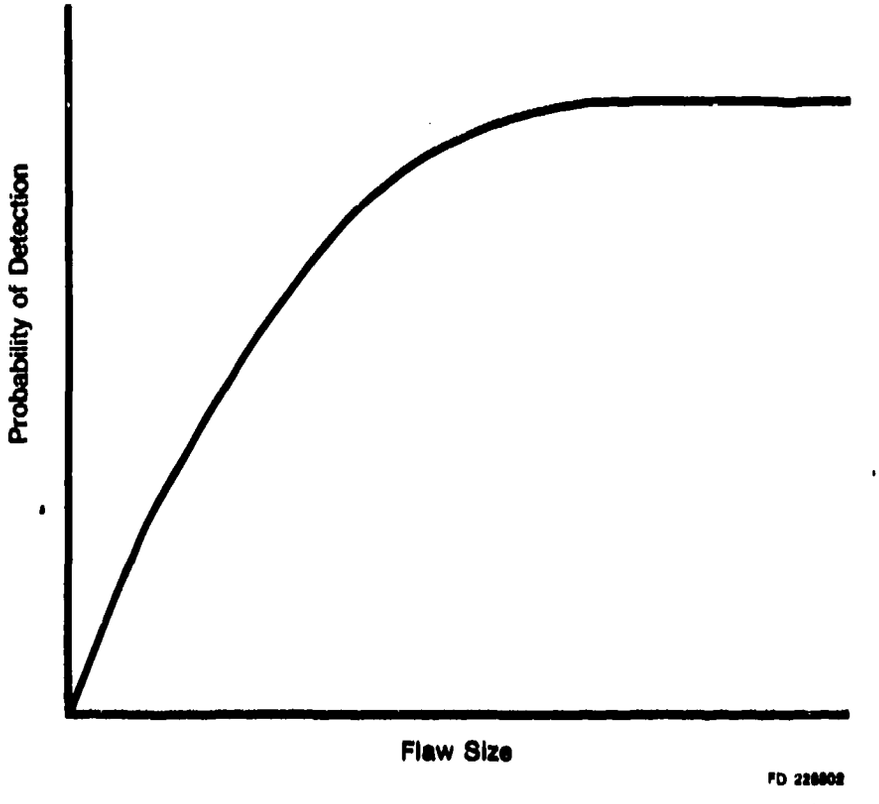


Figure 17. Probability of Detection Versus Flaw Size ($y = a(x)^b$ Expected Distribution)

In some cases, parametric statistics do not describe the data properly in which case nonparametric statistics should be used. The merits of nonparametric statistics include the fact that they are "distribution-free" and computationally simple; they may be used to describe data that is not inherently numerical but rather a qualitative ranking and can be used with small groups of data. Nonparametric statistics are far less widely used and, as a result, are unfamiliar to many people; the concept of "distribution-free" statistics is the most alien. The advantage of not having to assume a distribution is very helpful when the data does not appear to have any well known distribution, such as the data gathered in this program. This is especially useful in nondestructive evaluation data analysis since many factors, some of which are difficult to quantify, may or may not have a strong influence on detectability in any given sample. This characteristic can also be used to help compare such factors as Type II errors (false calls) and brightness. The property that rankings with no inherent numerical designation can be analyzed is useful in that brightness, a property seldom examined statistically, can be compared from one method to the next. The application to small groups of data is helpful in that a destructive test involving a limited number of samples can be performed while still yielding a significant amount of data. It must be emphasized that even though the approach is different from parametric statistics, the same types of information, such as upper and lower bounds on a mean, can generally be obtained.

The Freidman two-way analysis of variance by ranks, a nonparametric technique, is used to test the hypothesis that a group of samples come from the same population. This method is applicable to situations in which N samples are matched or studied under several (K) conditions. In this case, each specimen is associated with its point estimate of probability of detection for each of the three inspection runs. This data is then put into a table with N rows and K columns. The parameter of evaluation for each condition is found in one of the rows. The data in each row is ranked individually with a number from 1 to K. This process is continued until each row is ranked in this manner. The result is a table of numbers reflecting the relative sizes in each row, but not containing any actual data. Next, the columns are totaled into a set of sums denoted R_j. This test will compare the rank or column totals R_j for each condition tested. For reasonably sized samples, the chi squared distribution is a good approximation for the statistic χ_r^2 if df is taken as K-1 where

$$\chi_r^2 = \frac{12}{NK\,(K+1)} \sum_{j=1}^{k} (R_j)^2 - 3N\,(K+1)$$

N = number of rows
K = number of columns
R_j = sum of the ranks in the jth column
$\sum_{j=1}^{K}$ = sum of squares of the sum of the ranks for all conditions (K)

The statistic is then calculated and subsequently compared to the chi squared statistic at the level of significance of interest and the applicable conditions. The hypothesis can then be either accepted or rejected on the basis of this comparison. That is, if the chi squared value is smaller than the calculated number, the hypothesis can be rejected and the samples (runs) can be considered to be drawn from separate populations.

D. DATA ANALYSIS

The initial step in analyzing the data statistically is to plot the inspection data versus pertinent parameters. This step allows any obvious trends to be observed so they can be explored further with quantifiable methods later. The raw data plots yielded several interesting trends. A comparison of the data plots for the baseline and both improved runs indicates that a large increase in detectability occurred from the baseline to the improved surface preparation procedures inspection. In addition, a relatively small change appears between the improved surface preparation procedures inspection and the total modifications inspection. In addition, it is noted that practically all of the data appears at the POD of 1 or 0 indicating that the redundant inspections after a single processing had virtually no affect on detectability. This result is probably a function of the flaw size range as the transition region, where individual inspectors make a difference, did not appear in any of the data sets. Since the data appears in either the low detectability or high detectability range with no transition on any plot, the analytical models of the form $y = a\,(x)^b$ do not seem realistic for this problem. In addition, it does not appear that the POD changes with flaw size as approximately the same density of data points appear across the flaw size range. Also, the plots indicate that some very small flaws were found while much larger flaws were missed thus implying that more parameters are involved than flaw size. Such parameters could be crack tightness, smear metal, residual contamination, and material characteristics; the first three being very difficult to quantify in a practical sense.

To sort out which parameters have a strong influence on detectabilty, histograms were plotted with mean POD (number of finds/number of flaws) versus the parameter of interest. Initially, a comparison of the three runs graphically illustrates the large jump in detectability from baseline to the improved surface preparations and the relatively small change from improved surface preparations to total modifications. If the effect of material is examined, as in Figure 18, a large difference in detectability is noted between Titanium 6-4 and Inconel 718, the titanium blades showing the higher detectability. If a statistical difference between the two materials or geometries does exist, they should be analyzed separately to present a more accurate view of the actual data trends. Figures 19 and 20 show flaw size for each material broken down by run. This illustrates that probably no dependence between flaw size and detectability exists over this flaw size range. Both fine and coarse intervals were analyzed, both yielding the same trend. In addition, Figure 21 shows the intensity of the indications for each run. The large increase in brightness between the improved surface preparations and the total modifications should be noted. The number of false calls for each method is shown in Figures 22 and 23.

To make quantifiable statements about the trends noted from the data plots and the histograms, an analytical statistical procedure must be performed. Since the data does not appear to have any known distribution, nonparametric statistics have the best applicability as compared to a parametric variety. Nonparametric techniques can also allow the analysis of ranked quantities with no inherent numerical value, such as intensity. Because an easily quantified parameter (flaw length) does not appear to be related to detectability, nonparametric statistics is attractive.

The data was analyzed using the Friedman two-way analysis of variance by ranks method. Basically, this type of analysis tests the hypothesis that the samples have been drawn from the same population. Initially, the test was performed by material for each inspection run. The results indicate that the Ti-6Al-4V and Inconel 718 specimens are significantly different from a detectability standpoint; the Ti-6Al-4V was the most detectable. The difference could occur because the smear metal thickness may be greater on the Inconel 718 specimens resulting from the different material properties such as ductility and hardness.

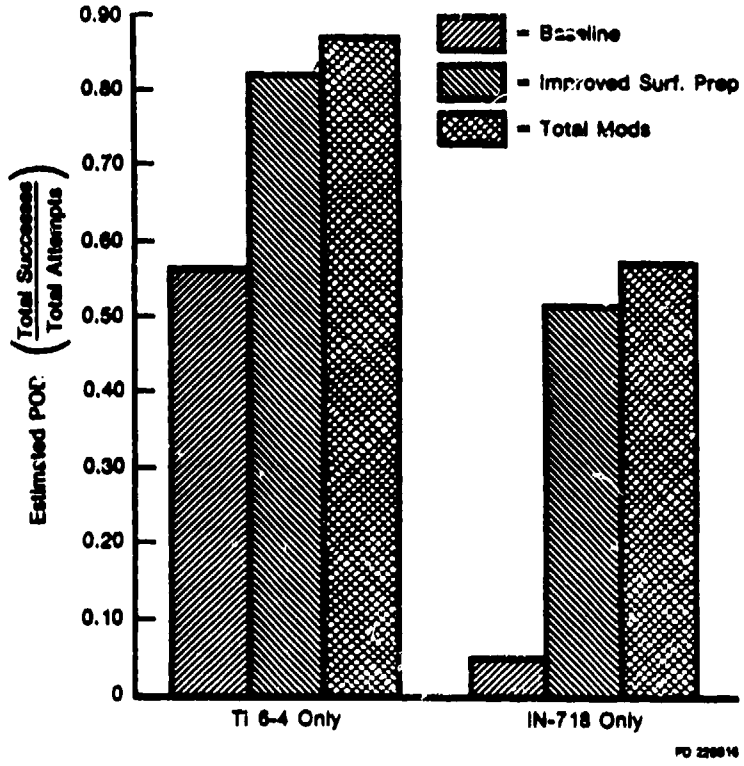


Figure 18. Histogram Comparing Detectability of Ti-6Al-4V and Inconel 718

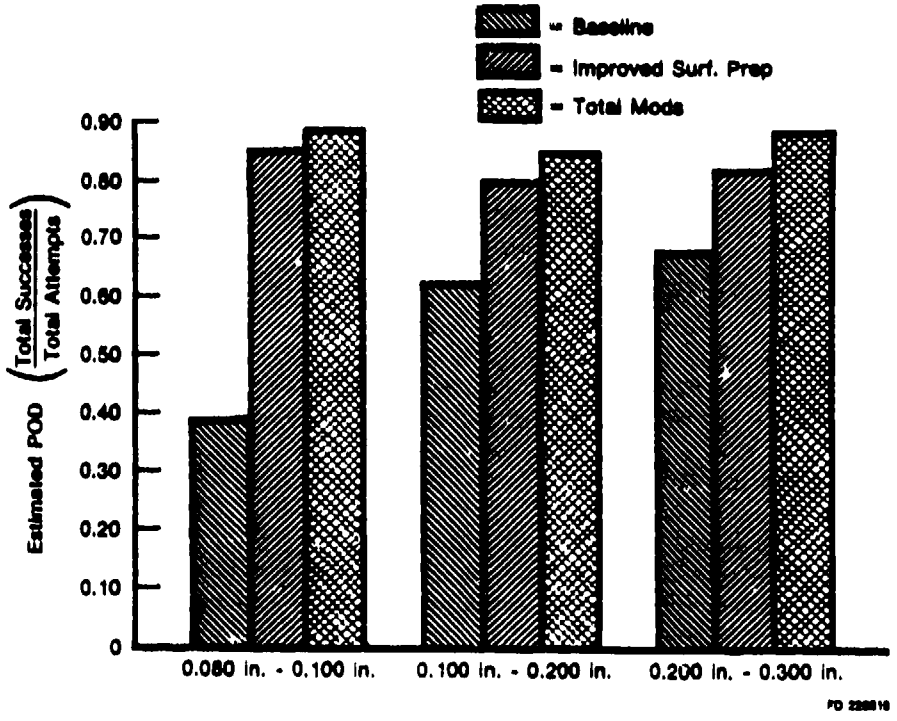


Figure 19. Histogram Comparing Detectability of Ti-6Al-4V for Each Run by Flaw Length

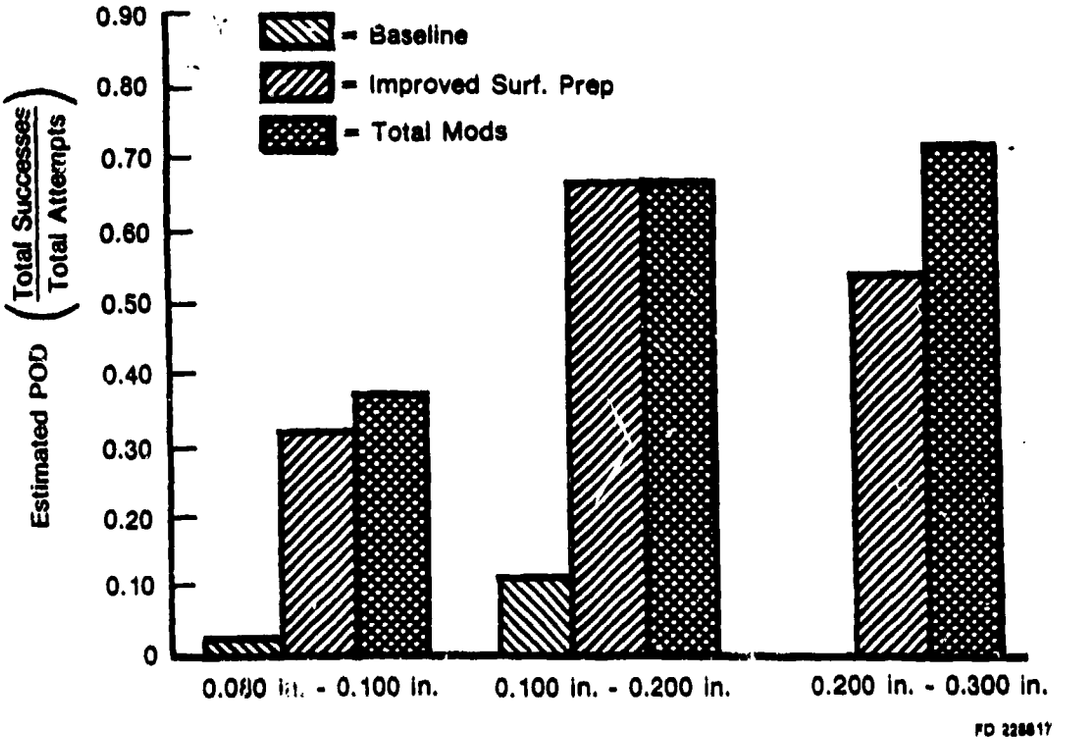


Figure 20. Histogram Comparing Detectabilities of Inconel 718 for Each Run by Flaw Length

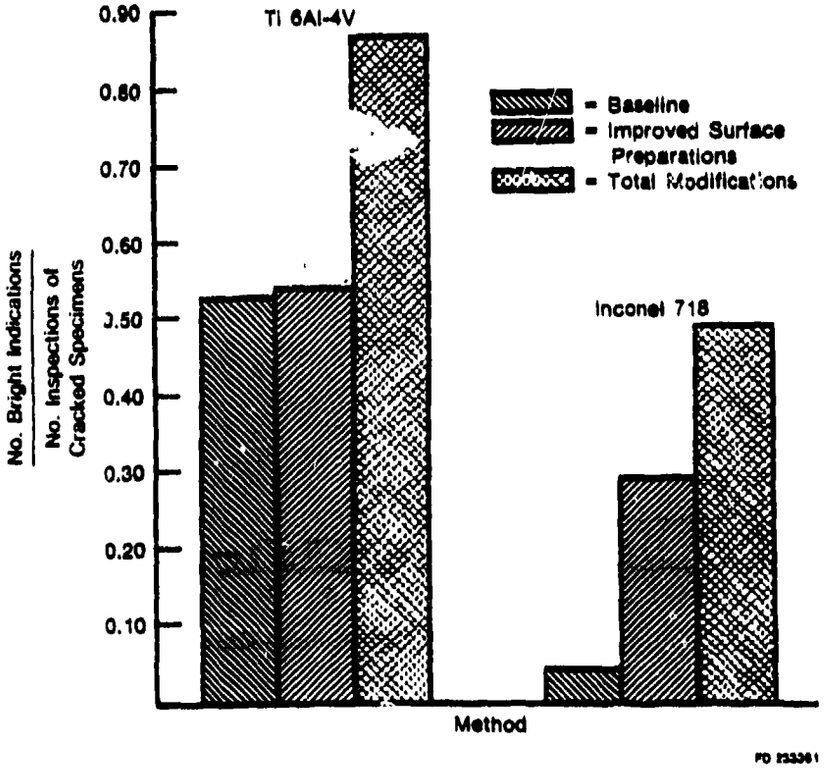


Figure 21. Histograms of Bright Indications Found by Each Methods

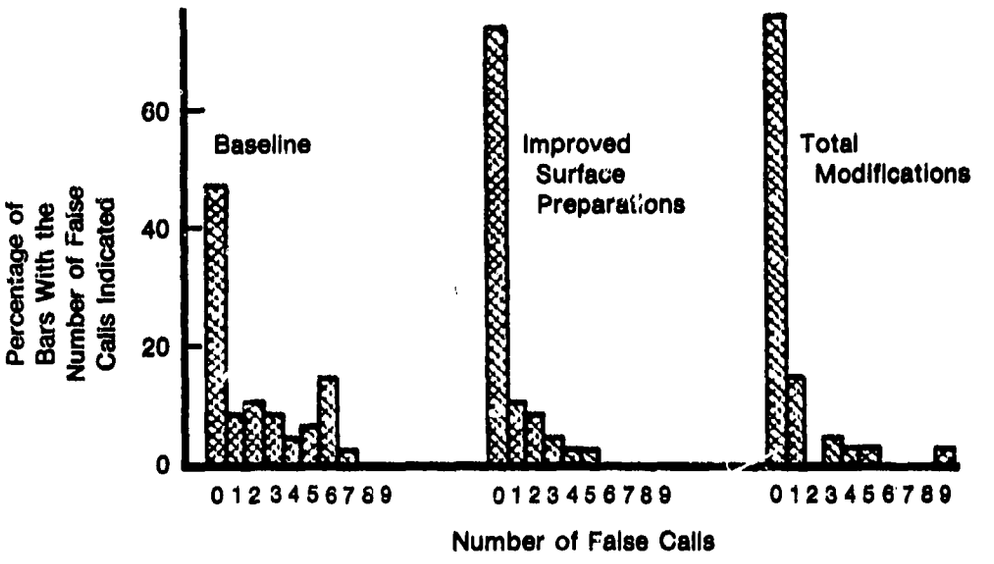


Figure 22. Histogram of False Calls for Inconel 718

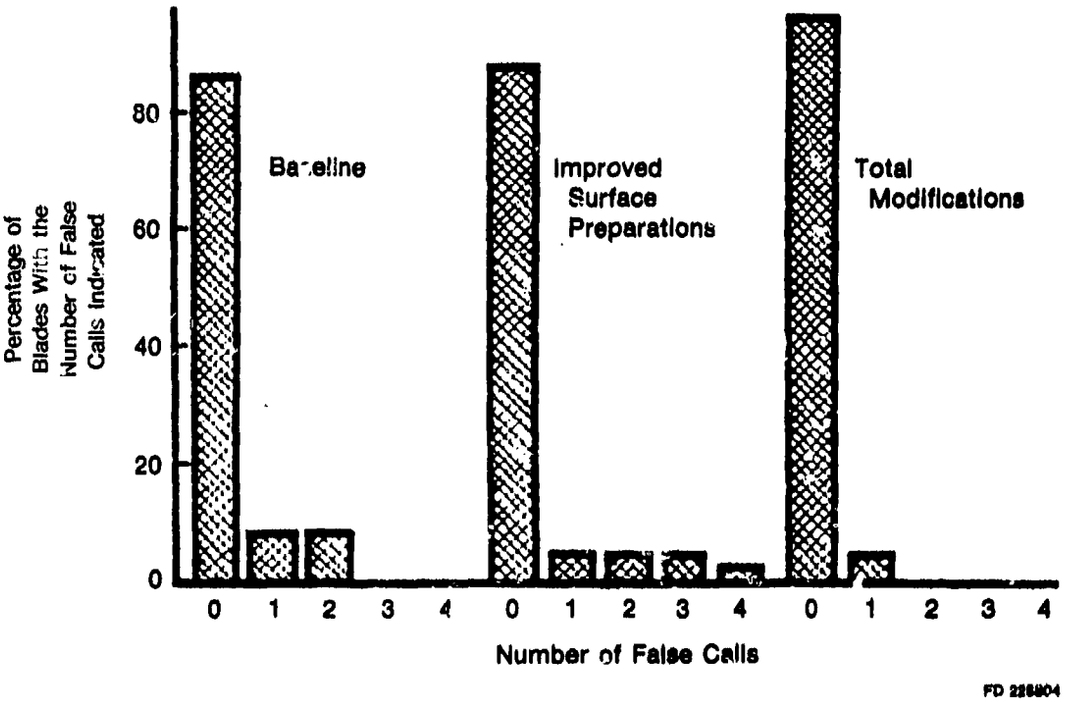


Figure 23. Histogram of False Calls for Ti-6Al-4V

After the demonstrations were completed, two Inconel 718 specimens were chemically milled repeatedly until an indication appeared. Following several etches one indication appeared to its full length while another appeared only as dots. The conclusion is that other effects such as crack tightness could have an influence on detectability, which also explains the lack of dependence of POD on flaw length. The cracks in the Inconel 718 bar specimens may be tighter as a result of having a thicker cross section than the blades. In addition, the bars were cracked in low cycle fatigue (higher stress level) while the blades were cracked in high cycle fatigue (lower stress level). The result is tighter cracks due to higher residual compressive stresses at the crack tips in the bar specimens. When the statistical test was applied to the detectability of the samples, the result was that both the Inconel 718 and Ti-6Al-4V showed a significant improvement from baseline to the improved surface preparations. Figures 24 and 25 illustrate the detectability graphically. For example, 90% of the data will have a mean POD greater than 0.47 for Ti-6Al-4V under baseline conditions (see Figure 24). In addition, the total improvements do not show a significant increase in detectability over the improved surface preparations for either material. It should be noted that relatively little room was left for increased detectability on the Ti-6Al-4V blades as the improved surface preparations increased the mean POD to a high level (0.82). In addition, the intensity of the indications was also analyzed. A significant difference was shown at a 90% level of significance between the total improvements and the improved surface preparations. Such an increase in brightness resulting from the modified process parameters is significant though detectability was not significantly increased. For the relatively large flaw sizes used in this program, the intensity is not an important factor in detectability; however, for relatively small flaw sizes the difference between a medium and a dim indication may well mean the difference between detecting a crack and passing over it. The occurence of false calls was also decreased significantly for Inconel 718 following the improved surface preparations. In all other cases, the initial number of false calls was low, not allowing a significant decrease. See Appendix for more information.

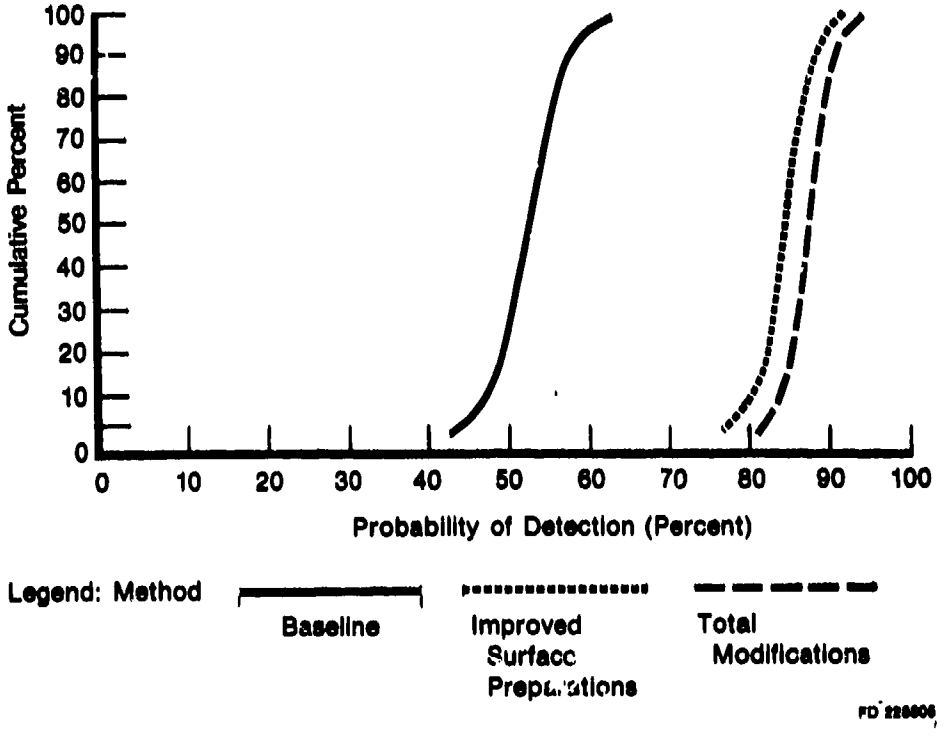


Figure 24. Cumulative Distribution Plot of Probability of Detection for Ti-6Al-4V

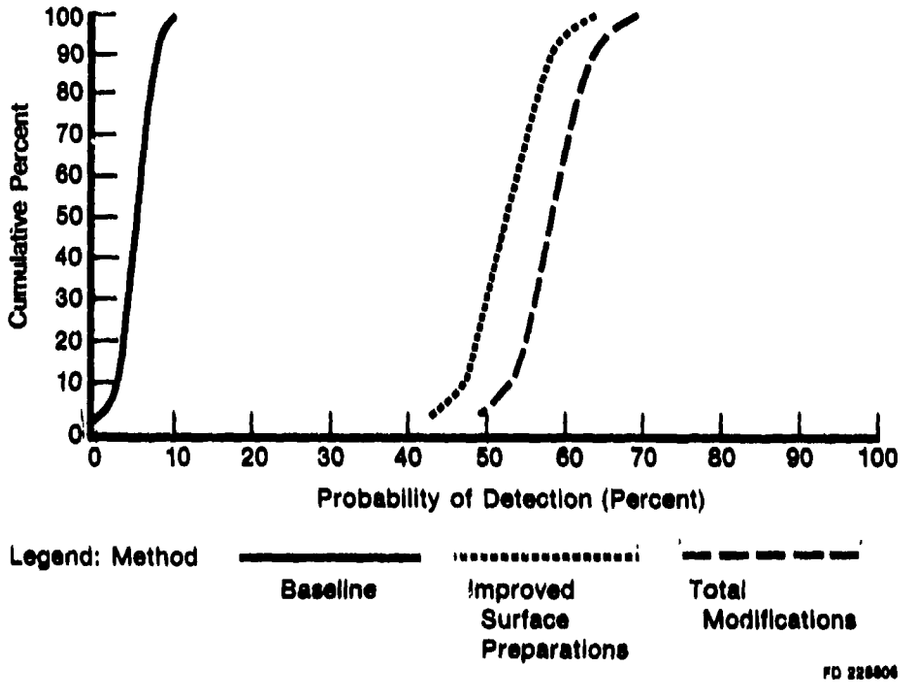


Figure 25. Cumulative Distribution Plot of Probability of Detection for Inconel 718

E. ASPECT RATIOS

After the specimens were all inspected following the demonstrations, twenty specimens were selected to be broken open to estimate the aspect ratio. The sample was based on detectability, flaw size, material, specimen geometry, and flaw location. Prior to fracturing, the specimens were heated to 315°C (600°F) for 30 minutes to allow the fracture surface to oxidize (heat tint) to facilitate measurements. The results are shown in Table 12 and a typical fracture surface of each variety is shown in Figures 26 and 27. An interesting side study was conducted during this procedure. The specimens with flaws that were known to be *undetectable* after the demonstrations were inspected with the modified process parameters after heat tinting. *All* of the flaws were detected following this procedure. Several days later, the specimens were inspected again and they remained detectable. To further investigate the effect of this heat tint cycle, several specimens were given a light vapor blast and inspected. No flaws were found. The heat tint cycle was then applied and the specimens were reinspected. The specimens showed no indications. The reason for this is not confirmed. Perhaps a thin layer of smear metal over a crack can be fractured by a thermal gradient induced by the smear metal heating more quickly than the base material, but this did not occur during the experiment.

The aspect ratios as well as flaw depths were also tested to determine if a correlation existed between these parameters and detectability. The results indicate that only a poor correlation exists such as that between flaw length and detectability. This result further enforces the notion that other parameters such as crack tightness and smear metal are very influential on detectability.

TABLE 12. ASPECT RATIOS OF FRACTURED SPECIMENS

Specimen Number	Crack Length cm	(in.)	Aspect Ratio	Specimen Type (Location)
15	0.203	(0.080)	2.66:1	Inconel Bar
43	0.820	(0.373)	6.2:1	Inconel Bar
52	0.521	(0.205)	4.0:1	Inconel Bar
91	0.343	(0.135)	2.68:1	Inconel Bar
202	0.305	(0.120)	2.68:1	Inconel Bar
218	0.249	(0.098)	2.38:1	Inconel Bar
227	0.630	(0.248)	2.27:1	Inconel Bar
164	0.516	(0.203)	4.4:1	Ti Blade (trailing edge)
118	0.315	(0.124)	1.5:1	Ti Blade (trailing edge)
145	0.724	(0.285)	2.78:1	Ti Blade (root)
121	0.277	(0.109)	2.93:1	Ti Blade (root)
59	0.533	(0.210)	3.44:1	Ti Blade (root)
63	0.584	(0.230)	3.83:1	Ti Blade (root)
76	0.479	(0.188)	2.86:1	Ti Blade (trailing edge)
86	0.381	(0.150)	3.75:1	Ti Blade (trailing edge)
87	0.386	(0.152)	5.43:1	Ti Blade (trailing edge)
77	0.239	(0.094)	1.06:1	Ti Blade (root)
170	0.236	(0.093)	2.05:1	Ti Blade (root)
197	0.457	(0.180)	2.94:1	Inconel Bar
221	0.368	(0.145)	3.08:1	Inconel Bar

Figure 26. Typical Fracture Surface of a Convex Side Root Crack in a Ti-6Al-4V Blade

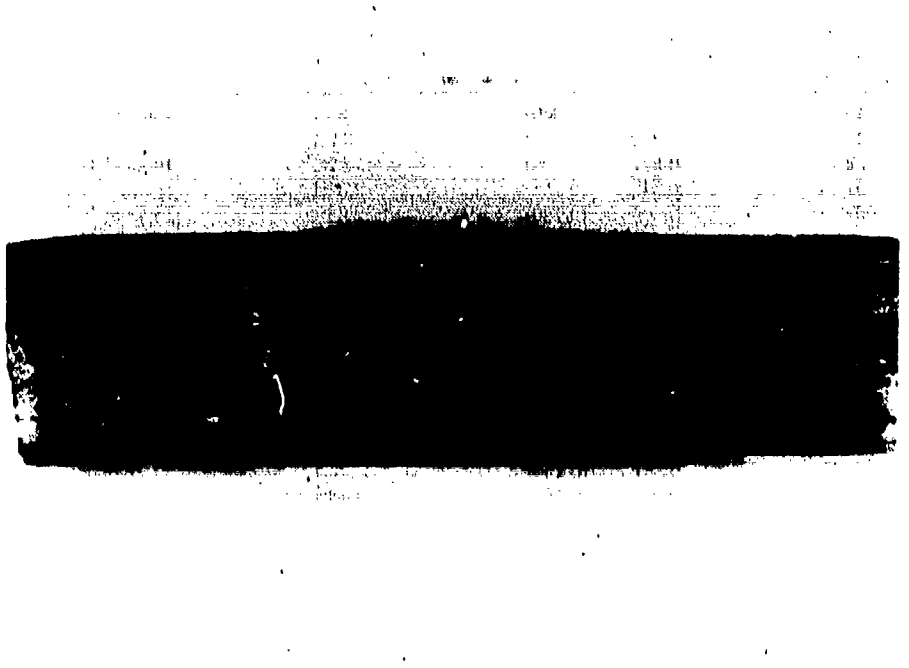


Figure 27. Typical Fracture Surface of a Crack in an Inconel 718 Bar

F. ENVIRONMENTAL CONCERNS

The procedures suggested by this program should not provide any different type of environmental concern than those currently dealt with on a day to day basis at an ALC. Corrosive agents are already in use and are being disposed of properly. As a result, the use of the acids suggested should not provide any additional safety or environmental hazard. Any change in process parameters should not cause an environmental concern as hydrophilic emulsifier in biodegradable and wet developer suggested is easier to contain than the dry developer currently in use.

SECTION III
CONCLUSIONS

1. The modified surface preparations of "Methods Improvement" significantly improved detectability over state-of-the-art surface preparation procedures. The improved surface preparations include chemically milling away a shallow smear metal layer (approximately 0.00254 mm to 0.00381 mm (0.0001" to 0.00015")).

2. The modified process parameters of "Methods Improvements" significantly increased the brightness of FPI indications over the state-of-the-art process parameters. The improvements included changes from lipophilic to hydrophilic emulsifier and from dry powder developer to water soluble wet developer.

3. Flaw length and the differences from inspector to inspector did not influence detectability for the parameters and flaw size range studied while other parameters such as crack opening and smear metal appear to be very influential.

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2. USAF T.O. 2J-TF39-3, Table 5-1.

3. NAVAIR 02-1-517/T.O. 2-1-111/DMWR 55-2800-206, also letter from Richard A. Shanahan, Specialized Engineering Branch, Engineering Division, D/MM of OC/ALC to Steve Cargill, P&WA/GPD, dated 7 May 1980 on Cleaning and FPI Procedure for Inconel 718 and Ti-6Al-4V.

4. "Nonparametric Statistics for the Behavioral Sciences," Sidney Siegal, McGraw-Hill, 1956.

APPENDIX
EXPLANATION OF STATISTICAL ANALYSES ILLUSTRATED IN FIGURES 24 AND 25

Figures 24 and 25 present data which may be used to establish upper and lower bounds for various confidence levels associated with the particular FPI demonstration conducted during this program. Probability of detection (number of defects found divided by the number of inspection opportunities) is presented on the X-axis of each plot. Values along the Y-axis represent the estimated percentage of times that the corresponding mean probability of detection would be achieved if the experiment were performed many times. The typical value of interest is the lower bound on probability of detection at a particular confidence level (i.e., the one tailed distribution case). To find the lower bound on the curves shown, the desired confidence level is subtracted from 100% and the resulting value is found on the Y-axis. The corresponding probability of detection value is the lower bound for the technique at the given confidence level. For example, in Figure 24, the 90% confidence lower bound for the baseline case is 48% probability of detection. By using confidence levels and lower bounds, decisions can be made about the difference between two populations. If the mean of one population is greater than the lower bound of the second population, the first population can not be said to have significantly lower level of probability of detection than the second population. Specifically, in Figure 24, the mean of the "improved surface preparations" technique is 85% and the lower bound of the "total modifications" technique is 83% at 90% confidence. As a result it can be said that there is no statistically significant difference between "improved surface preparations" and "total modifications."